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Effective Discharge Calculation: A Practical Guide

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE) as part of the Flood Damage Reduction Research Program. The guidelines developed herein were products of Work Units 32776 "Channel Response and Channel-Forming Discharge" and 32878 "Channel Restoration Design." The Program Monitor was Mr. Richard J. DiBuono, HQUSACE. The Program Manager was Ms. Carolyn Holmes, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC). Principal investigators for the work units were Drs. David S. Biedenharn and Ronald R. Copeland, CHL.

The report was prepared by Dr. David S. Biedenharn, and Dr. Ronald R. Copeland, CHL, Dr. Colin R. Thorne, and Mr. Philip J. Soar, University of Nottingham, Dr. Richard D. Hey, University of East Anglica, and Dr. Chester C. Watson, Colorado State University. Data review and analysis was provided by Ms. Dinah N. McComas, CHL.

The study was performed under the supervision of Mr. Michael Trawle, former Chief of the River Sedimentation Branch, Dr. Phil G. Combs, former Chief of the Rivers and Structures Division, and Dr. James R. Houston, former Director, CHL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James S. Weller, EN, was Commander.

Conversion Factors, SI to Non-SI Units of Measurement

SI units of measurement used in this report can be converted to Non-SI units as follows:

Multiply	By	To obtain
meters	3.281	feet
cubic meters	35.32	cubic feet
square kilometers	0.39	square miles
tonne	1.1	US ton

Summary

An alluvial river adjusts the dimensions of its channel to the wide range of flows that mobilize its boundary sediments. However, in many rivers it has been demonstrated that a single representative discharge can be used to determine a stable channel geometry. The use of a single representative discharge is the foundation of "regime" and "hydraulic geometry" theories for determining morphological characteristics of alluvial channels and rivers. This representative discharge has been given several names by different researchers including *dominant* discharge, *channel-forming* discharge, *effective* discharge, and *bankfull* discharge. This has led to some confusion. In this report the channel forming discharge and the dominant discharge are equivalent and are defined as a theoretical discharge that if maintained indefinitely would result in the same channel geometry as the existing channel subject to the natural range of flow events. Although conceptually attractive, this definition is not necessarily physically feasible, because bank line vegetation, bank stability and even the bed configuration would be different in a natural stream than in a constant discharge stream. Channel-forming discharge concepts are applicable to stable stream systems, i.e., streams that are neither aggrading or degrading.

Channel-forming discharge can be estimated using one of three prescribed methodologies. One such deterministic discharge is the bankfull discharge, which is the discharge that fills the channel to the top of its banks. Another deterministic discharge used to represent the channel-forming discharge is a specified recurrence interval discharge, typically between the mean annual and five-year peak. This report focuses on a third approach to determine the channel-forming discharge, known as the effective discharge. The effective discharge transports the largest fraction of the bed material load. Because of this, the effective discharge can be a good estimator for channel-forming discharge.

All three methodologies for estimating channel-forming discharge provide challenges. In practice, identification of bankfull elevation along a reach of channel in the field is often problematic. If nearby gauge data are not available, bankfull discharge must be calculated using an assumed hydraulic roughness. Likewise, correlating recurrence interval and bankfull discharge has been shown to vary widely for different types of streams. The calculation of effective discharge requires historical hydrologic and sediment data. Without nearby gauge data, effective discharge calculations require using an assumed hydraulic roughness and determining a reliable sediment transport equation.

Equivalence of bankfull and effective discharges has been demonstrated for naturally stable alluvial channels in a wide variety of river types (sand-bed, gravel-bed, cobble-bed and boulder-bed) and in different hydrological environments (perennial, humid and slightly ephemeral, and semiarid). However, this equivalence may not hold for truly ephemeral streams in semi-arid or arid areas.

The procedure for effective discharge calculations presented herein has been developed for a range of river types. It is a systematic method designed to have general applicability, and to integrate the effects of the physical processes responsible for determining stable channel dimensions. The effective-discharge should not be assumed to be the channel-forming discharge a priori without confirmation using field indicators of geomorphic significance. It is good practice to also determine the bankfull discharge where possible, and to develop a frequency curve, and to cross-check the estimates for channel-forming discharge to reduce the uncertainty in the final estimate.

Applications of the effective discharge concept outlined in the report include a fully worked example of the calculations, a channel stability assessment, a channel management application, and an application to restoration design.

1 Channel-Forming Discharge Concept

Alluvial rivers have the potential to adjust their shape and dimensions to all flows that transport sediment, but Inglis (1941) suggested that for rivers that are in regime, a single steady flow could be identified which would produce the same bankfull dimensions as the natural sequence of events. He referred to this flow as the dominant discharge, which is equivalent to the term channel-forming discharge used in this report.

Based on field observations, Inglis (1947) determined that the channel-forming discharge was approximated by flows at or about bankfull stage. This finding has been supported by subsequent research (Nixon 1959, Simons and Albertson 1960, Kellerhals 1967, Hey and Thorne 1986). These studies have not, however, explained why bankfull flow controls channel form.

To explain this phenomenon it is necessary to recognize that any local imbalance in the sediment budget must generate change in the morphology of an alluvial river through either erosion or deposition. Hence, to remain dynamically stable, the regime dimensions of the channel must be adjusted so that, over a period of years, sediment input and output are balanced. During this time, Wolman and Miller (1960) showed that rivers adjust their bankfull capacity to the flow transporting the most sediment. That flow was named the effective discharge (Andrews 1980).

Wolman and Miller (1960) found that the effective discharge corresponds to an intermediate flood flow since frequent minor floods with both shorter durations and smaller peaks transport too small a sediment load to have a marked impact on the gross features of the channel, while catastrophic events, which individually transport large sediment loads, occur too infrequently to be effective in forming the channel. The potential for large floods to disrupt the regime condition and cause major channel changes is recognized by this concept, but large floods are not the channel-forming events, provided that the return period of these extreme events is longer than the period required for subsequent, lesser events to restore the long-term, average condition (Wolman and Gerson 1978).

In humid environments, perennial rivers usually recover their long-term, average morphology within 10 to 20 years following a major event, principally because riparian and floodplain vegetation limits the impacts of major floods and

because vegetation regrowth encourages the processes of siltation involved in morphological recovery (Gupta and Fox 1974; Hack and Goodlett 1960). In semiarid regions, the recovery period tends to be longer, reflecting both the reduced effectiveness of sparse vegetation in increasing the channel's resilience to change and the sensitivity of the channel to the occurrence of wet and dry periods (Schumm and Lichty 1963, Burkham 1972). In arid areas, the largest floods leave long lasting imprints on the channel because of the lack of vegetation and because lesser events capable of restoring a regime condition rarely occur (Schick 1974).

Equivalence between bankfull and effective discharges for natural alluvial channels that are in regime has been demonstrated for a range of river types (sand, gravel, cobble and boulder-bed rivers) in different hydrological environments (perennial, humid and slightly ephemeral, and semiarid) provided that the flow regime is adequately defined and the appropriate component of the sediment load is correctly identified (Andrews 1980; Carling 1988; Hey 1997). The equivalence of bankfull and effective discharges for stable channels suggests that either one could be used to define the channel-forming discharge. Also, in theory, channel-forming discharge could be determined indirectly from an estimate of the return period for either bankfull flow or the effective discharge.

In practice, major problems are likely to arise when attempting to use bankfull discharge to determine the channel-forming discharge. Problems center on the wide range of definitions of "bankfull stage" that exist (Williams 1978). Although several criteria have been identified to assist in field identification of bankfull stage, ranging from vegetation boundaries to morphological breaks in bank profiles, considerable experience is required to apply these in practice, especially on rivers which have undergone aggradation or degradation.

In many studies channel-forming discharge is estimated from the recurrence interval for bankfull discharge. Leopold and Wolman (1957) suggested that the bankfull flow has a recurrence interval of between one and two years. Dury (1973) concluded that the bankfull discharge is approximately 97 percent of the 1.58-year discharge, or the most probable annual flood. Hey (1975) showed that for three British gravel-bed rivers, the 1.5-year flow in an annual maximum series passed through the scatter of bankfull discharges measured along the course of the rivers. Richards (1982) suggested that, in a partial duration series, bankfull discharge equals the most probable annual flood, which has a one-year recurrence interval.

In practice, bankfull discharge is often assumed to have a recurrence interval of about 1.5 years and recently Leopold (1994) stated that most investigations have concluded that the bankfull discharge recurrence intervals range from 1.0 to 2.5 years. However, there are many instances where the bankfull discharge does not fall within this range. For example, Pickup and Warner (1976) determined that bankfull recurrence intervals may range from 4 to 10 years in the annual maximum series. Therefore, extreme caution must be used when estimating the channel-forming discharge using a flow of specific recurrence interval.

Problems associated with field identification of the bankfull elevation and the choice of an appropriate recurrence interval are eliminated when the effective discharge approach is employed. To determine the effective discharge, both an annual flow-duration curve and a sediment-discharge rating curve are required. The basic approach is to divide the range of discharges into a number of equal arithmetic classes and then calculate the total sediment load for each flow class. This is achieved by multiplying the frequency of occurrence of each flow class by the median sediment load for that flow class. The mean of the flow class with the greatest sediment load is the effective discharge.

Although the channel-forming discharge concept is not universally accepted, most river engineers and scientists agree that the concept has merit, at least for perennial and slightly ephemeral streams in humid and semiarid environments. On the basis of this review, it is concluded that there are three approaches to determining the channel-forming discharge: a) bankfull discharge, b) flow of a given recurrence interval, and c) effective discharge.

Ideally, the method used to determine the channel-forming discharge should have general applicability, should have the capability to be applied consistently, and should integrate the physical processes responsible for determining the channel dimensions. There are limitations for each of these methods that the user must recognize. The selection of the appropriate method will be based on data availability, physical characteristics of the site, level of study and time and funding constraints. If possible, it is recommended that all three methods be used and cross-checked against each other to reduce the uncertainty in the final estimate.

This report outlines the best practical procedure for performing the necessary calculations to determine the effective discharge.

2 Effective Discharge Calculation

Hydrological Data

A standardized procedure is required to ensure that effective discharge calculations are accurate and that results from different sites can be compared. To be practical, the procedure must use only data which are readily available from gauging stations, or which can be synthesized using limited additional computations.

The basic approach is to divide the range of riverflows during the period of record into a number of arithmetic classes and then calculate the total sediment quantity transported by each class. This is achieved by multiplying the frequency of occurrence of each flow class by the median sediment load for that flow class (Figure 1). The initial data required are flow-duration data and a sediment transport rating curve.

The calculated value of the effective discharge depends to some extent on the steps used to manipulate the input data to define the flow regime and sediment transport function. The procedure described represents "best practice" in this regard, based on extensive firsthand experience in using flow and sediment transport data to determine the effective discharge.

Gauged sites

The first step in an effective discharge calculation is to group the discharge data into equal arithmetic flow classes and determine the number of events occurring in each class during the period of record. Logarithmic or non-equal width arithmetic classes introduce systematic bias into the calculation of effective discharge and should not be used. Grouping the discharge data is usually accomplished using a flow-duration curve, which is a cumulative distribution function of observed discharges at the gauging station. For example, Figure 2 is a flow-duration curve for the Sevier River, UK. The flow duration curve defines the percentage of time a particular discharge is equaled or exceeded. The frequency of occurrence of each discharge class is calculated from this curve. Three critical components must be considered when developing a flow-duration

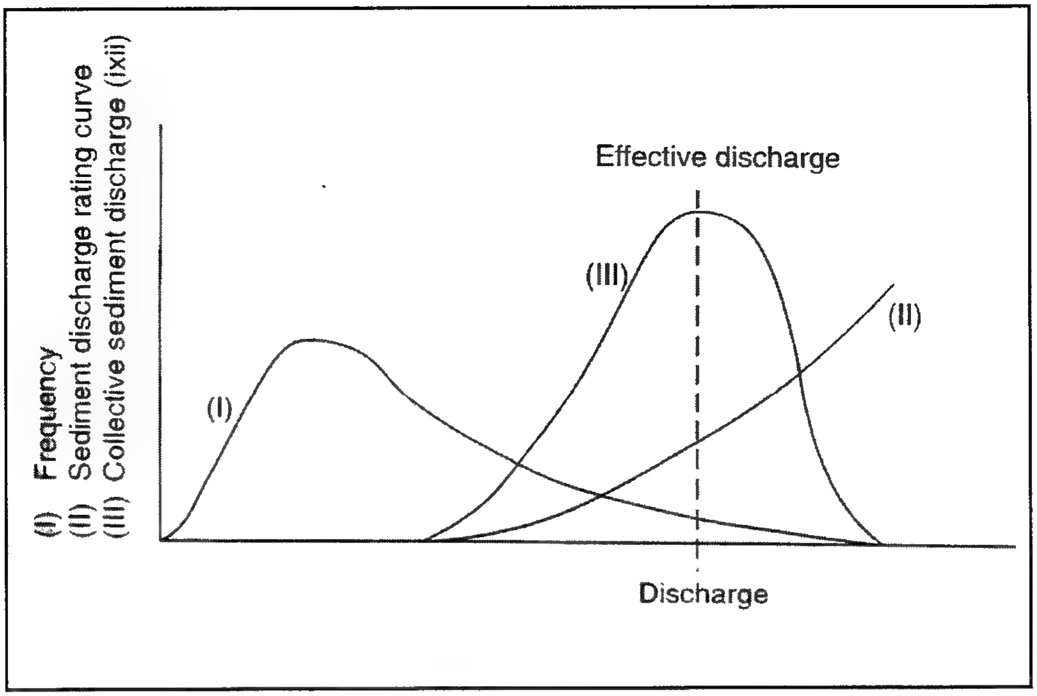

Figure 1. Derivation of total sediment load-discharge histogram (iii) from flow frequency (i) and sediment load rating curves (ii)

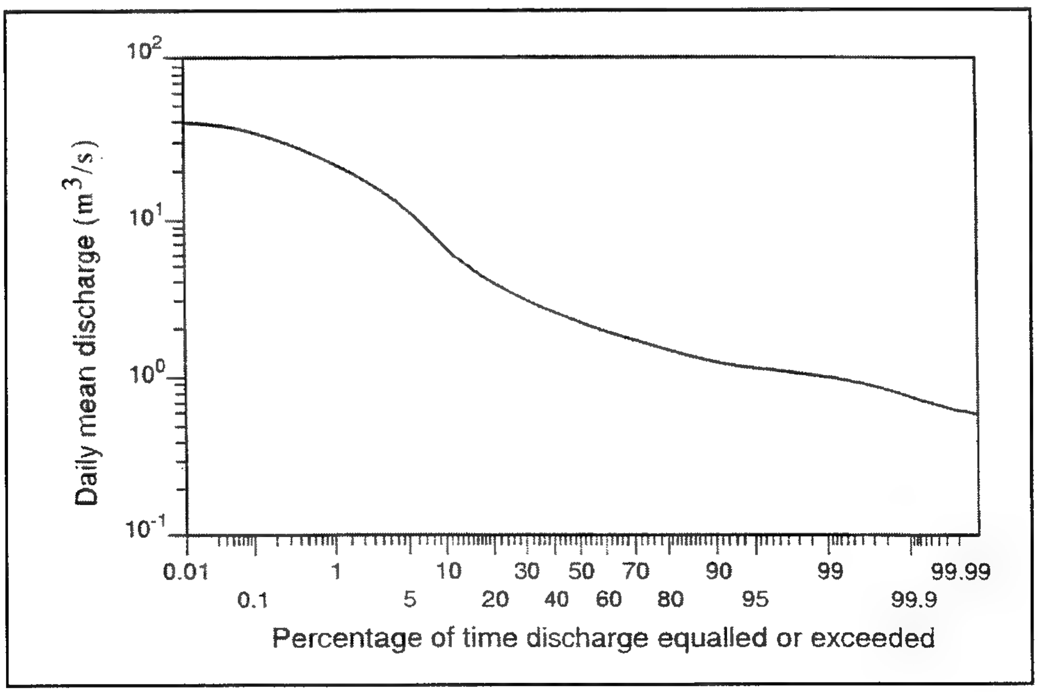

Figure 2. Daily mean flow duration curve: Sevier River, Hatch, UK (Hey 1997)

curve: the number of discharge classes; the time base for discharge averaging; and the length of the period of record. It is important that the historical record is homogeneous, i.e. watershed conditions are unchanged.

Class interval and number of classes. The selection of class interval can influence the effective discharge calculation. Intuitively, it may be expected that the smaller the class interval and, therefore, the greater the number of classes, the more accurate would be the outcome. However, when too small an interval is used, discontinuities appear in the discharge frequency distribution. These in turn produce a rather irregular sediment-load histogram, which has multiple peaks. Therefore, the selected class interval should be small enough to accurately represent the frequency distribution of flows, but large enough to produce a continuous distribution.

There are no definite rules for selecting the most appropriate interval and number of classes, but Yevjevich (1972) stated that the class interval should not be larger than s/4, where *s* is an estimate of the standard deviation of the sample. For hydrological applications he suggested that the number of classes should be between 10 and 25, depending on the sample size.

Hey (1997) found that 25 classes with equal arithmetic intervals produced a relatively continuous flow frequency distribution and a smooth sediment-load histogram with a well defined peak, indicating an effective discharge which corresponded exactly with bankfull flow. A smaller interval, and correspondingly larger number of classes, produced anomalous results. Experience has shown that in some cases, 25 classes produce unsatisfactory results and that up to 250 classes may be required. Particular care has to be exercised on rivers where there is a high incidence of very low flows as, for example, on the Little Missouri River at Marmarth and Medora (Hey 1997). Under these circumstances, the effective discharge may be biased towards the lowest discharge class.

Time base. Mean daily discharges are conventionally used to construct the flow-duration curve. Although this is convenient, given the ready availability of mean daily discharge data from the United States Geological Survey (USGS), it can, in some cases, introduce error into the calculations. This arises because mean daily values can underrepresent the occurrence of short-duration, high magnitude flow events that occur within the averaging period, while overrepresenting effects of low flows.

On large rivers, such as the Mississippi, the use of the mean daily values is acceptable because the difference between the mean and peak daily discharges is negligible. However, on smaller streams, flood events may last only a few hours, so that the peak daily discharge is much greater than the corresponding mean daily discharge. Excluding the flood peaks and the associated high sediment loads can result in underestimation of the effective discharge. Rivers with a high flashiness index, defined as the ratio of the instantaneous peak flow to the associated daily mean flow, are more likely to be affected. To avoid this problem it may be necessary to reduce the time base for discharge averaging from 24 hours (mean daily) to 1 hour, or even 15 minutes on flashy streams. For example, an investigation of discharge data for 11 USGS gauging stations in the

Yazoo River Basin, Mississippi revealed that the annual yields of bed-material calculated using mean daily discharge data were approximately 50 percent less than the yields calculated using 15 minute data (Watson, Dubler, and Abt 1997). These are relatively small basins (drainage areas less than 1,000 km^2) with high rainfall intensities and runoff characteristics that have been severely affected by land-use change and channel incision. Consequently, hydrographs are characterized by steep rising and falling limbs, with events peaking and returning to base flow in much less than 24 hours.

In practice, mean daily discharge data may be all that are available for the majority of gauging stations and these data may be perfectly adequate. However, caution must be exercised when using mean daily data for watersheds with flashy runoff regimes and short-duration hydrographs. The use of 15-minute data to improve the temporal resolution of the calculations should be seriously considered whenever the available flow records allow it.

In the absence of 1 hour or 15-minute data, recorded hydrographs from USGS gauging records can be used to refine the high discharge portion of the flow-duration curve. Actual instantaneously recorded hydrographs can be used to determine durations of the highest discharges in the historical record.

Period of record. The period of record must be sufficiently long to include a wide range of morphologically-significant flows, but not so long that changes in the climate, land-use or runoff characteristics of the watershed produce significant changes with time in the data. If the period of record is too short, there is a significant risk that the effective discharge will be inaccurate due to the occurrence of unrepresentative flow events. Conversely, if the period is too long, there is a risk that the flow and sediment regimes of the stream at the beginning of the record may be significantly different to current conditions.

A reasonable minimum period of record for an effective discharge calculation is about 10 years, with 20 years of record providing more certainty that the range of morphologically significant flows is fully represented in the data. Records longer than 30 years should be examined carefully for evidence of temporal changes in flow and/or sediment regimes. If the period of record at a gauging station is inadequate, consideration should be given to developing an effective discharge based on regional estimates of the flow duration.

Ungauged sites

At locations where gauging records are either unavailable or are found to be unrepresentative of the flow regime, it will be necessary to synthesize a flow-duration curve. There are two possible methods of doing this. The first method is by using records from nearby gauging stations within the same drainage basin. The second is developing a regionalized flow-duration curve.

It must be recognized that these methods simply provide an approximation of the flow-duration characteristics, and that there can be considerable uncertainty in the results. The reliability of these methods is a function of the quality of the existing gauge data and the morphologic similarity between the gauged and ungauged locations. Caution is advised whenever the existing gauge data are limited, or the site in question has a significantly different morphologic character than the gauged site.

Drainage area, flow-duration curve method. This method relies on the availability of gauging station data at a number of sites on the same river as the ungauged location. First, flow-duration curves for each gauging station are derived for the longest possible common period of record. This guarantees comparability between the data, as all the gauging stations have experienced the same flow conditions, and ensures that the curves represent the longer period. Provided there is a regular downstream decrease in the discharge per unit watershed area, then a graph of discharge for a given exceedance duration against upstream drainage area will produce a power function with virtually no scatter about the best-fit regression line. For example, Figure 3 shows this relationship for the River Wye, UK (Hey 1975). The equations generated by this method enable the flow-duration curve at an ungauged site on that river to be determined as a function of its upstream watershed area.

For sites on streams where there is only one gauging station, flow duration curves can be estimated at ungauged locations provided the streams are tributaries to rivers where the relation between discharge and drainage area conforms to a known power function. Estimates of the contributing flow to the mainstem can be obtained from the difference between discharges on the mainstem above and below the tributary junction. Discharge - drainage area relations can then be derived for the tributary given the flow-duration curve at the gauging station and the predicted curve at its confluence with the mainstem. However, this technique should not be used if there are distinct and abrupt downstream changes in the discharge per unit area for the watershed. This could occur if portions of the drainage area consisted of different hydrological regions. In this case it would be preferable to use the regionalized duration curve method described in the next paragraph.

Regionalized duration curve method. An alternative to the use of watershed area to generate a flow duration curve for an ungauged site is to use a regional-scaling method based on data from watersheds with similar characteristics. For example, Emmett (1975) and Leopold (1994) suggest using the ratio of discharge to bankfull discharge (Q/Q_b) as a non-dimensional index to transfer flow-duration relationships between basins with similar characteristics. However, bankfull discharge does not necessarily have either a consistent duration or return period (Williams 1978).

To avoid this problem, a non-dimensional discharge index was proposed by Watson, Dubler, and Abt (1997) using the regionalized 2-year discharge to normalize discharges (Q/Q_2). For ungauged sites the 2-year discharge may be estimated from regionalized discharge frequency relationships developed by the

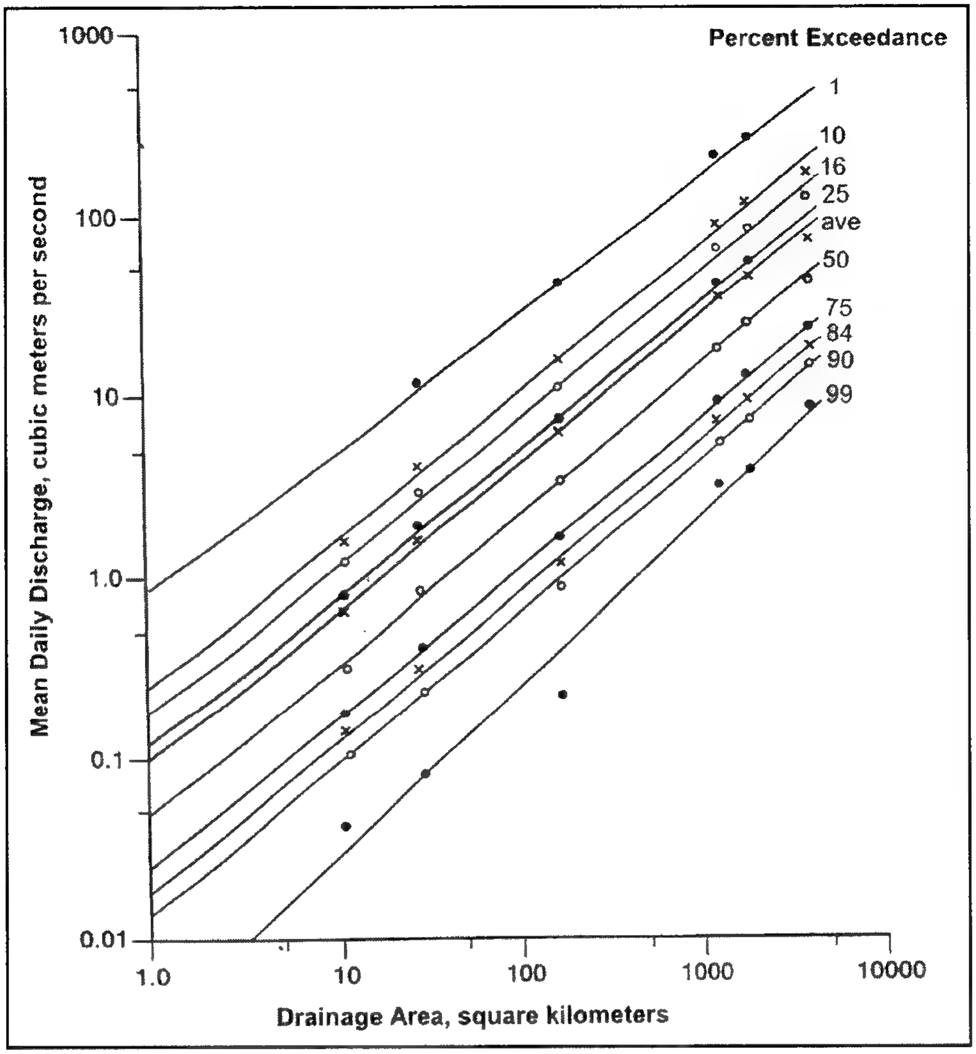

Figure 3. Downstream daily flow-duration curves: RiverWye, UK 1937-1962 (Hey 1975)

USGS (1993) on the basis of regression relationships between the drainage area, channel slope, and slope length. These relationships are available for most states.

The dimensionless discharge index (Q/Q_2) can be used to transfer a flow-duration relationship to an ungauged site from a nearby gauged site. The gauged site may be within the same basin, or an adjacent watershed.

To transfer a flow-duration relationship within a watershed use the following steps:

a. Develop the regionalized flow-duration curve. Using a flow-duration curve from a gauged site in a physiographically similar watershed, divide the discharges in the flow-duration relationship by the Q_2 for the gauged site. This creates a dimensionless flow-duration curve. If more than one

gauge site is available an average dimensionless flow-duration curve for all the sites can be developed.

b. Compute the Q_2 for the ungauged site.

c. Calculate the flow-duration curve for the ungauged site. Multiply the dimensionless ratios from the regionalized flow-duration curve by the ungauged Q_2.

Sediment Transport Data

Nature of the sediment load

The total sediment load of a stream can be broken down on the basis of measurement method, transport mechanism or source as shown in the following diagram. When discussing the sediment load of a stream, it is important to keep track of the terminology adopted and the nature of the load being discussed.

Measurement Method	Transport Mechanism	Sediment Source
Unmeasured Load	*Bed Load*	*Bed Material Load*
Measured Load	*Suspended Load*	
		Wash Load

Sediment transport data: gauged sites

In most alluvial streams the major features of channel morphology are principally formed in sediments derived from the bed-material load. It is, therefore, the bed-material load which should be used in an effective discharge calculation.

At gauged sites the measured suspended load usually contains most of the suspended load, but excludes the bed load. Under these circumstances, the coarser fraction of the measured suspended load (generally the sand load - i.e. particles larger than 0.062 mm) should be used to derive a bed-material load rating curve. If available, bed load data should be combined with the coarse fraction of the measured suspended load to derive a bed-material load rating curve.

Where a significant proportion of the bed-material load moves as bed load (such as in gravel-bed rivers) but no measurements of bed load are available, it may be necessary to estimate the bed load. This may be achieved using a suitable bed-load transport equation. The U.S. Army Corps of Engineer hydraulic design package, SAM, (Copeland, et al. 1997) can be used to make these calculations.

Similarly, at gauging stations with no measured sediment load data at all, a bed-material sediment rating curve may be generated using appropriate sediment transport equations.

Sediment transport data: ungauged sites

At ungauged sites it will be necessary to generate a bed-material sediment rating curve. The application of a suitable sediment transport equation is vital and the SAM package is helpful because it includes guidance on the selection of equations best suited to the type of river and bed-material in question (Raphelt 1990). An example of this approach is given in Watson, Dubler, and Abt (1997).

Figure 4 shows the resulting calculated sand discharges for several water discharges together with the measured sand fraction load, and a rating curve based on regression of the measured data. Close agreement is apparent between the Brownlie computation of the bed-material load and the regression line based on the observed USGS sand fraction data.

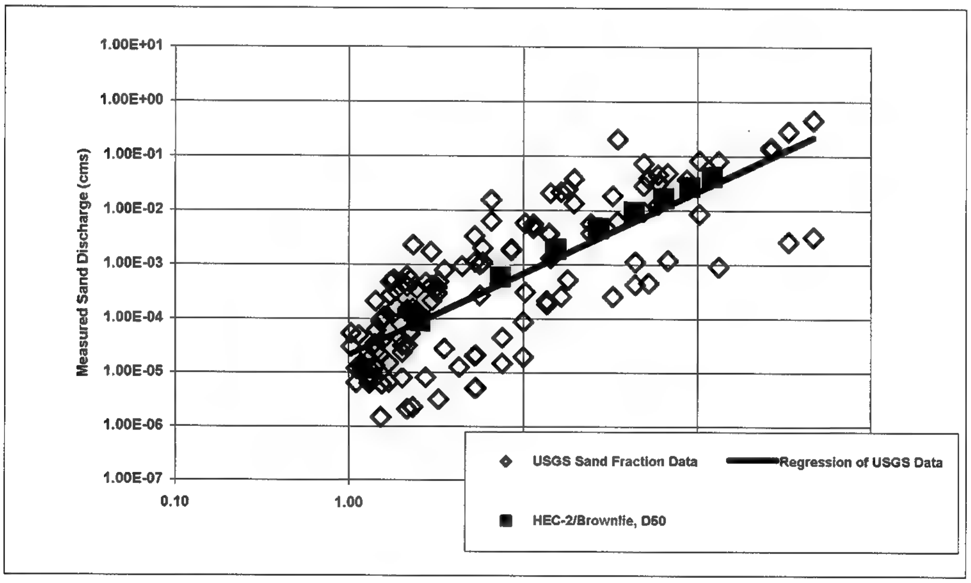

Figure 4. Comparison of sediment relationships for Abiaca Creek, Site no. 6 (Watson, Dubler, and Abt 1997)

Computational Procedure

The recommended procedure to determine the effective discharge is executed in three steps. In Step 1, the flow-frequency distribution is derived from available flow-duration data. In Step 2, sediment data are used to construct a bed-material load rating curve. In Step 3, the flow-frequency distribution and bed-material load rating curve are combined to produce a sediment-load histogram, which

displays sediment load as a function of discharge for the period of record. The histogram peak indicates the effective discharge.

Flow frequency distribution

a. *Evaluate flow record.* The flow record is a historic record of discharges at a gauging station. The record from a single gauging station can be used to develop the flow-frequency distribution if the gauge is in close proximity to the project reach and the discharge record at the gauge is representative of the flow regime in the project reach. It is also important that watershed conditions have remained unchanged during the selected flow period. If a gauging record is either unavailable or unrepresentative, then the flow-frequency distribution can be derived using either the basin-area method or the regionalized duration curve method.

b. *Check the period of record.* It is recommended that the length of the period of record be at least 10 years and that measurements be continuous to the present day. Discharge data can still be used if there are short gaps in the record, but caution must be exercised when collecting data from a discontinuous record. The flow-frequency curve will not be representative of the natural sequence of flows over the medium term if the length of record is less than 10 years or if the record has been influenced by changes in the watershed runoff regime. If this is the case, a flow-duration curve should be developed using the methods described in "ungauged sites."

c. *Determine the discharge-averaging time base.* To construct the flow-frequency distribution, the time base should be sufficiently short to ensure that short-duration, high magnitude events are properly represented. If 15-minute data are unavailable, then either 1 hour or mean daily data can be used, but caution must be exercised when using mean daily data to develop a flow frequency distribution for a stream exhibiting a flashy regime.

d. *Calculate discharge range.* The discharge range is calculated by subtracting the minimum discharge in the flow record from the maximum discharge.

e. *Calculate discharge class size.* It is recommended that the initial attempt to construct the flow-frequency distribution should use 25 classes and an arithmetic scale class interval. Therefore, the class interval is the discharge range, calculated in Step (d), divided by 25. The class interval should not be approximated by rounding. The relative proportions of the bed-material load moving in suspension and as bed load should be estimated during site reconnaissance. For rivers in which the bed-material load moves predominantly as suspended load, the first discharge class goes from zero to the class interval; the second class is determined by adding the class interval to the upper value of the previous class and

so on until the upper limit of the discharge range is reached. For gravel-bed rivers, where bed-material load moves predominantly as bed load, the minimum discharge used in generating the flow-frequency distribution should be set equal to the critical discharge for the initiation of bed-load transport.

f. *Calculate flow frequency distribution.* The frequency of occurrence for each discharge class is determined from the record of observed flows. It is more convenient to convert the actual frequency to percentage frequency. To do this multiply the actual value for each discharge class by 100 and divide by the total number of recorded flows in the discharge record. The percentage frequency represents the proportion of the flow record falling within the upper and lower limits of each discharge class. If a regional flow-duration curve has been developed for an ungauged site, the frequency for each discharge class must be calculated using the equation for the curve. This can be achieved by calculating the geometric mean discharge of each discharge class and deriving the percentage frequency from the equation. On the flow-duration curve, this is the probability of each discharge being equaled or exceeded.

g. *Check for extreme flow events.* It is recommended that all discharge classes display flow frequencies greater than zero and that there are no isolated peaks in individual classes at the high end of the range of observed discharges. If this is not the case, it is likely that either the class interval is too small for the discharge range, or the period of record is too short. Both zero frequencies and extreme flow events (outliers) can be eradicated by reducing the number of classes. Steps e and f are repeated to generate the flow-frequency distribution for the new class intervals. The computational procedure for generating a flow frequency distribution is outlined in Figure 5.

Bed-material load rating curve

a. *Determine sediment data availability.* Sediment data are required to generate the bed-material load rating curve. These data may be obtained from measurements at a gauging station if the gauge is in close proximity to the project reach and if size-class fractions are provided so that the bed-material portion of the measured load can be determined. A bed gradation from the project reach is required to determine the division between wash load and bed-material load, and to calculate sediment transport if necessary.

b. *Define composition of bed-material load.* The wash load should be excluded from the data set used to develop the rating curve. If the bed-material load moves both as bed load and suspended load, then both bed load and suspended-load measurements are required to determine the bed-material load. If measured load data are insufficient, appropriate

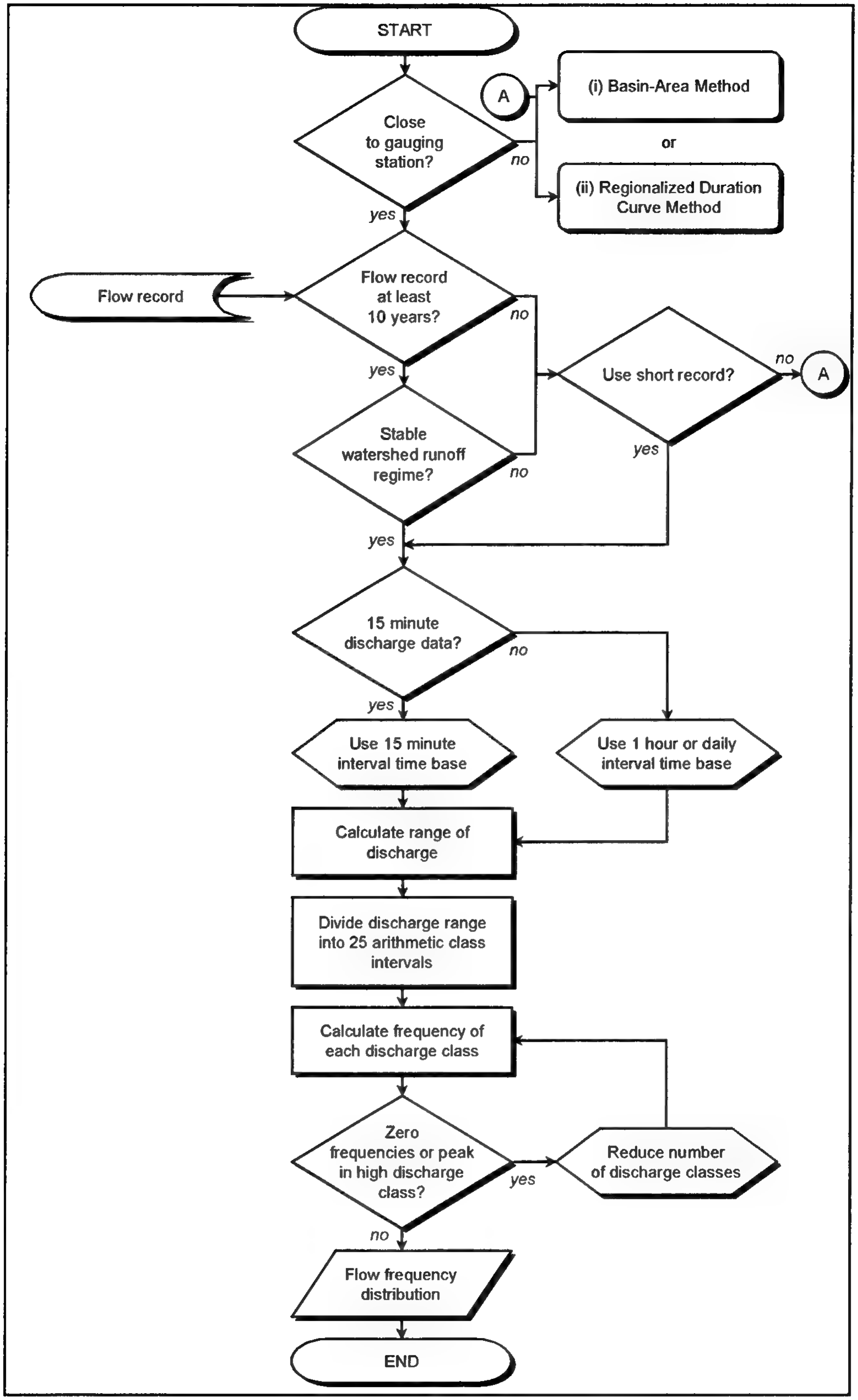

Figure 5. Computational procedure for generating a flow-frequency distribution

equations in the hydraulic design package SAM (Copeland et al. 1997), can be used to generate bed-material loads for selected discharges.

c. *Determine bed-material load.* In streams dominated by suspended load, a best-fit regression curve, fitted to the data, may be adequate to produce a bed-material load function. Frequently this takes the form of a power function:

$$Q_s = a\,Q^b$$

where Q_s is the bed-material load discharge, Q is the water discharge, a is a regression coefficient, and b is a regression exponent. However, a straight line power function may not be appropriate in all cases. Sometimes, at high discharges the rate of increase in sediment concentration with discharge begins to decrease, especially for the finer sand sizes. In this case it may be necessary to use a different curve fitting function. In coarse bed streams it is likely that a coarse surface layer will develop at lower discharges, significantly reducing sediment transport potential. This process involves both hydraulic sorting of the stream bed and hiding of small particles behind bigger particles. Typically, calculated sediment transport rating curves developed from a single-bed gradation will overestimate sediment transport at low discharges. This is probably the most important reason for too much sediment being calculated in the lower discharge class intervals. The computational procedure for generating a bed-material load rating curve, is diagrammed in Figure 6.

Bed-material load histogram

a. *Calculate representative discharges.* The discharges used to generate the bed-material load histogram are the mean discharges in each class in the flow frequency distribution.

b. *Construct the bed-material load histogram.* The histogram is generated by using the representative discharges and the bed-material load rating curve to find the bed-material load for each discharge class and multiplying this load by the frequency of occurrence of that discharge class. The results are plotted as a histogram representing the total amount of bed-material load transported by each discharge class during the period of record. This calculation can be completed using the sediment yield routine in the SAM hydraulic design package.

c. *Calculate effective discharge.* The bed-material load histogram should display a continuous distribution with a single mode (peak). If this is the case, the effective discharge corresponds to the mean discharge for the modal class (the peak of the histogram). If the modal class cannot be readily identified, the effective discharge can be estimated by drawing a smooth curve through the tops of the histogram bars and interpolating the effective discharge from the peak of the curve.

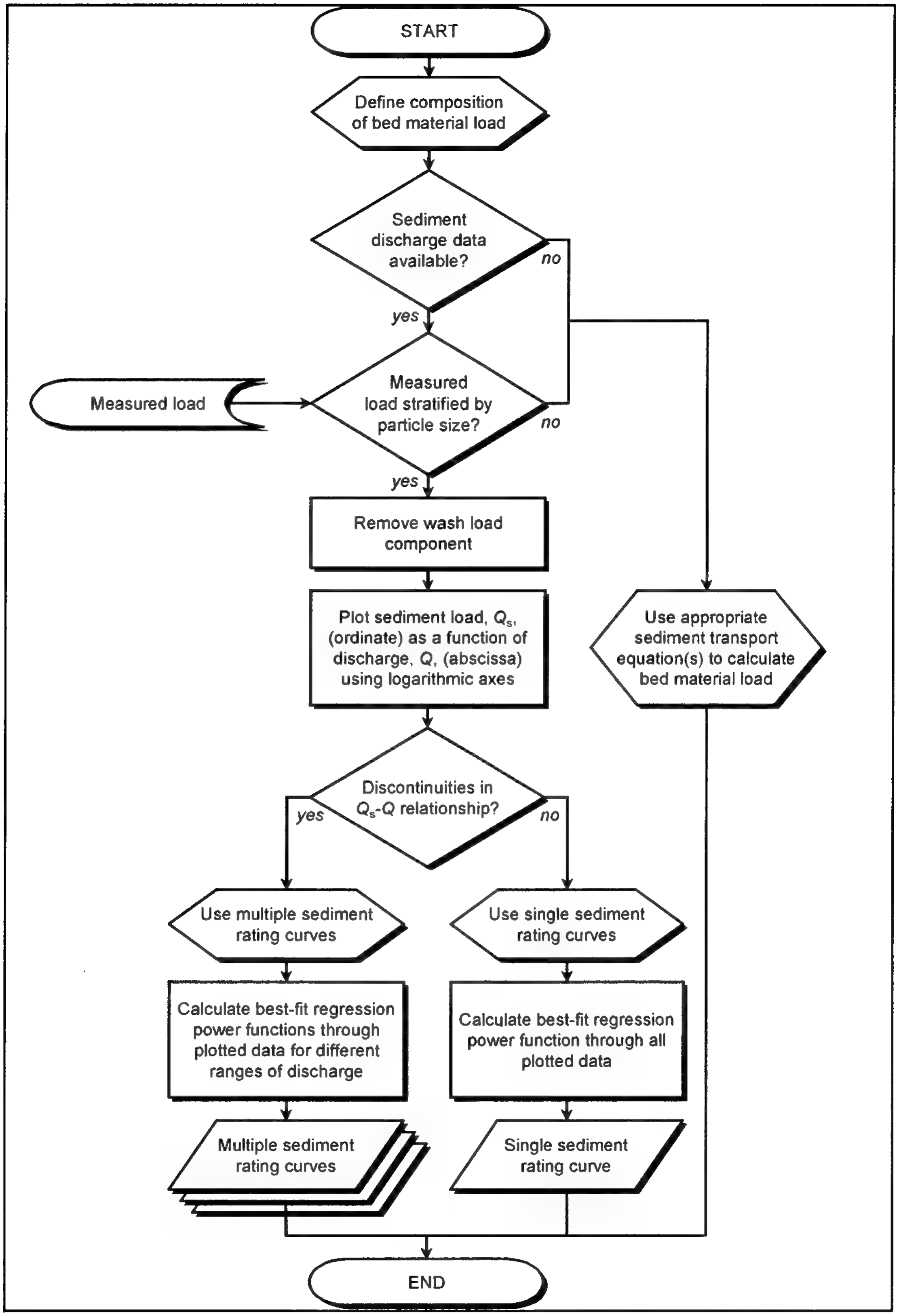

Figure 6. Computational procedure for generating a bed-material load rating curve

d. *Evaluate the bed-material load histogram.* If the modal class of the bed-material load histogram is the lowest discharge class, it is likely that the indicated effective discharge is erroneous. In this case, it may be necessary to modify the procedure by increasing the number of discharge classes or modifying the bed-material rating curve, noting the cautions to be exercised in each case.

e. *Check if the calculated effective discharge is reasonable.* At the end of the procedure, it is important to check that the effective discharge is a reasonable value for the project reach. Suitable ranges of the channel forming flow return period have been reported in the literature and guidance is given in Chapter 3. A further check is to compare the duration of the effective discharge with basin area-flow duration curves. Finally, a morphological check should be undertaken to compare the effective discharge to the bankfull discharge. This is best performed by identifying the bankfull stage at a stable cross-section and calculating the corresponding discharge either from the stage-discharge relationship at a nearby gauging station, or using the slope-area method. The computational procedure for generating a bed-material load histogram, is diagrammed in Figure 7.

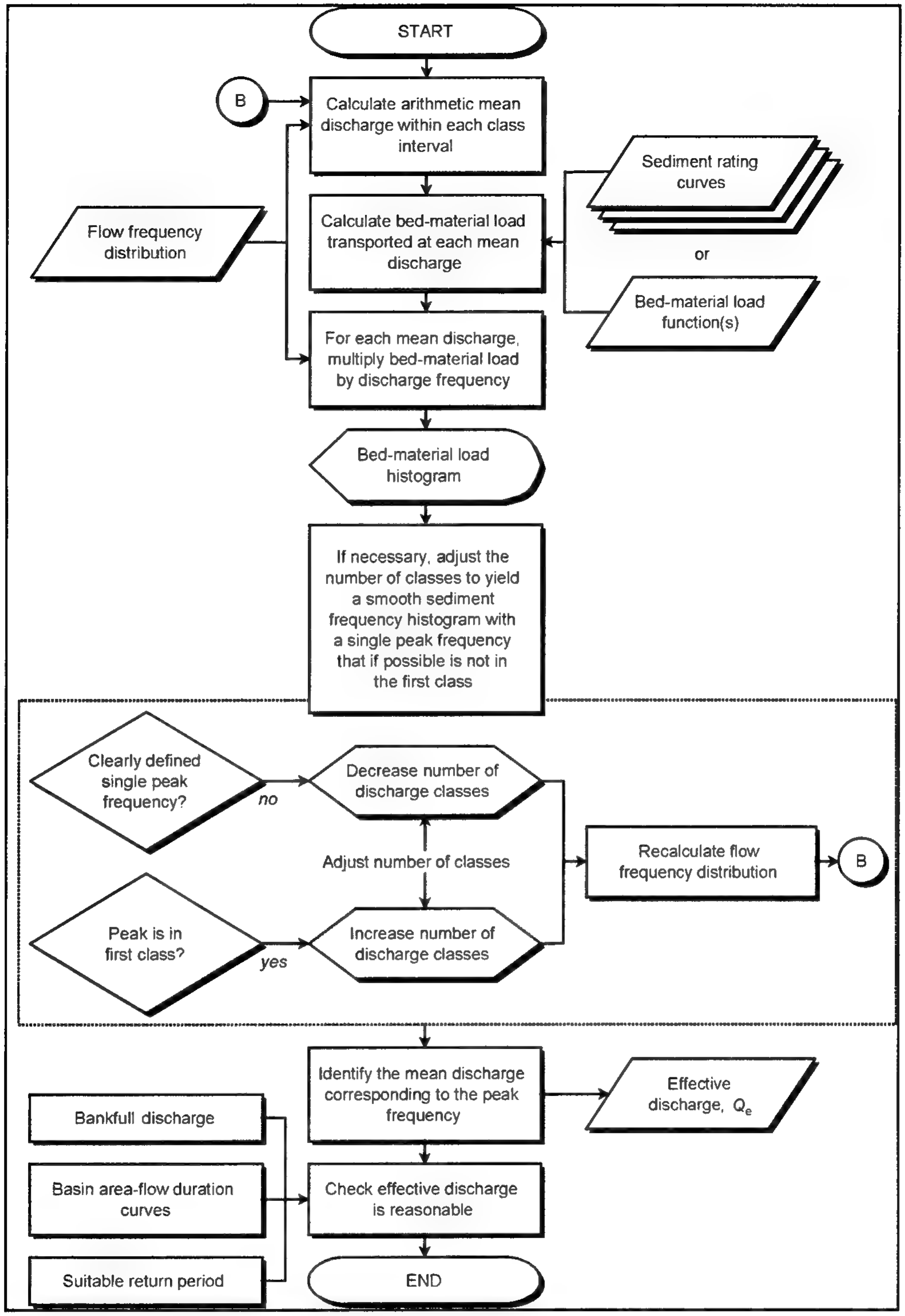

Figure 7. Computational procedure for generating a bed-material load histogram

3 Evaluation and Problem Solving

Problems with Lowest Discharge Class

When a significant proportion of the recorded discharges fall within the first arithmetic class interval of the flow-duration curve, the range of discharges is inadequately represented and it is likely that the computed effective discharge will be significantly underestimated. This is likely the case for streams displaying a highly skewed distribution of flow events, for example, rivers in semiarid environments, channelized streams, or incised channels. Under these circumstances, it is advisable to increase the number of class intervals to better define the flow-duration curves.

Problem with Outliers

Discharge records, especially those based on mean daily values, can contain distinct gaps in the higher discharge categories due to the averaging process. This is likely on rivers with flashy hydrographs or if there has been an extremely large flood event during a short period of record. The use of arithmetic discharge class intervals can produce a discontinuous flow-frequency distribution which in turn generates an irregular bed-material load histogram with outliers that reflect the transport associated with individual flood events. The danger is that the wrong peak may be selected to represent the modal class, leading to serious overestimation of the effective discharge.

When there are only a few high discharges in the record it is possible to end up with too many high discharge events in one class and no events in adjacent classes. This results in unrealistic gaps in the bed-material load histogram. The problem can usually be solved by increasing the class interval and reducing the number of classes. This reduces the number of discharge classes with zero bed-material load and removes the outliers, smoothing the histogram. For example, on the White River upstream of Mud Mountain Dam, when 40 class intervals were used, the effective discharge was indicated to be unrealistically high (387 m^3s^{-1}). This problem was solved by reducing the number of classes to 25, resulting in an effective discharge of 81 m^3s^{-1}, which corresponded to bankfull flow (Hey 1997).

Checking Effective Discharge

Guidance on return periods for the effective discharge

The return period for the effective discharge is expected to vary between sites depending on the flow and sediment-transport regime of the individual river or reach. For sites where annual maximum series flood-flow data are available, the return period of the calculated effective discharge may be checked to ensure that it lies within acceptable bounds.

Unfortunately, there is very limited information available regarding the return period of the effective discharge for stable rivers. Experience indicates that it lies within the range 1.01 and 3 years with a preponderance between 1.01 and 1.2 years, irrespective of the type of river (Hey 1997). There is more information on the return period of bankfull flow and, as this is equivalent to the effective discharge for rivers that are in regime, it may be taken to define the general range of likely return periods for the effective discharge. Despite the lack of consensus regarding the definition of bankfull stage (Williams 1978), which can significantly affect calculated return periods, available data indicate that 78 percent of bankfull flow return periods are in the range 1.01 to 3.0 years, with a modal value in the 1.01- to 1.20-year category (Hey 1994). Predicted effective discharge return periods outside the range of approximately 1- to 3-years should be queried.

Drainage area – flow-duration curve

The percentage of time the effective discharge is equaled or exceeded should be compared to the expected range of values reported in the literature.

For example, Figure 8 presents a log-log plot of the flow duration of effective discharge as a function of drainage area for several U.S. rivers (Watson, Dubler, and Abt 1997). The graph can be used to assess whether the duration of the effective discharge computed using the method described in this manual is comparable to the results of other studies. It is not intended that this graph be used to predict effective discharge as a function of drainage area, as large errors are likely to result from this application.

Check effective discharge against bankfull discharge

The effective discharge should be compared to the bankfull discharge. This can be accomplished by identifying the bankfull stage during stream reconnaissance of the project reach and calculating the corresponding discharge, as outlined in Step e of "Bed-material load histogram."

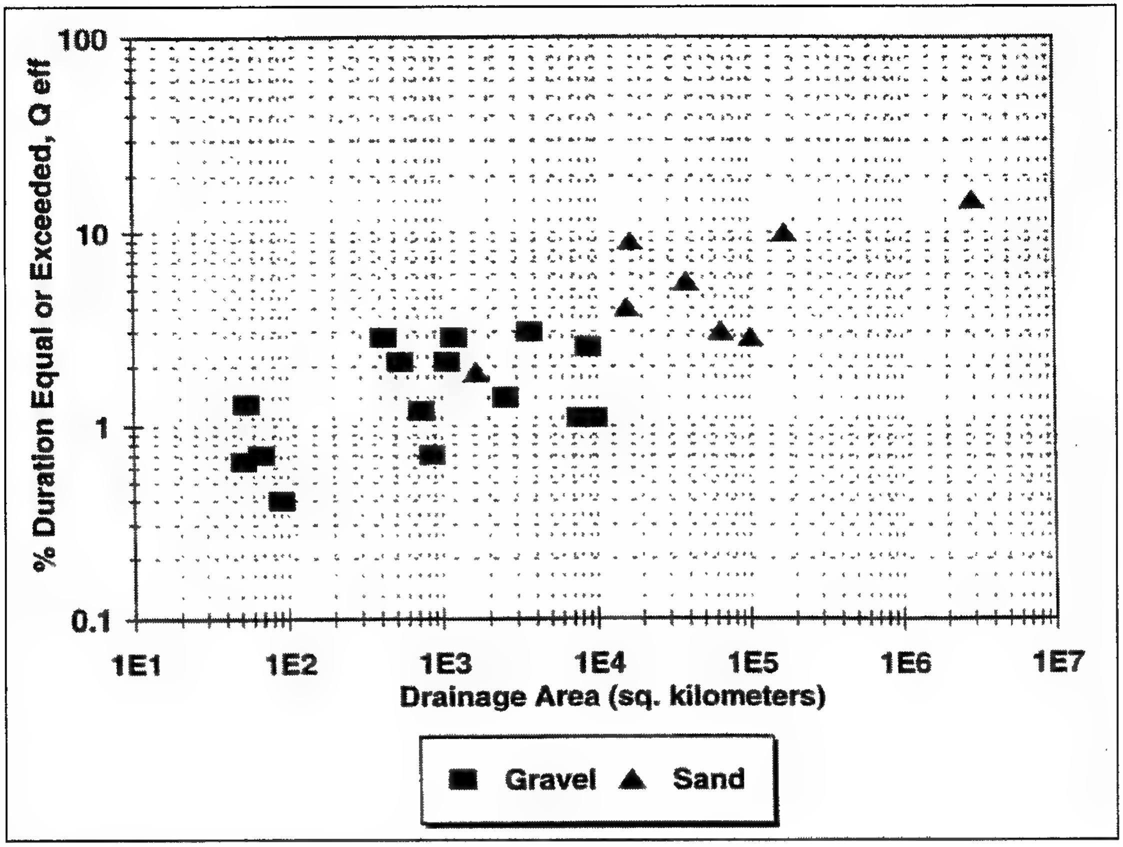

Figure 8. Effective discharge duration versus drainage area

4 Applications

Effective Discharge Calculation for the Mississippi River at Vicksburg

Flow frequency distribution

Discharge data were obtained from the Vicksburg gauge for the period 1950 to 1982. This period of record was selected as it encompasses the period when sediment loads were routinely measured at the gauging station. The record contains a wide distribution of flows including both low and high runoff years and with discharges ranging from about 4,200 to just over 56,600 m^3s^{-1}. On this large river, mean daily discharges do not differ significantly from instantaneous discharges so the use of mean daily values was acceptable in the production of the flow-frequency distribution (Figure 9).

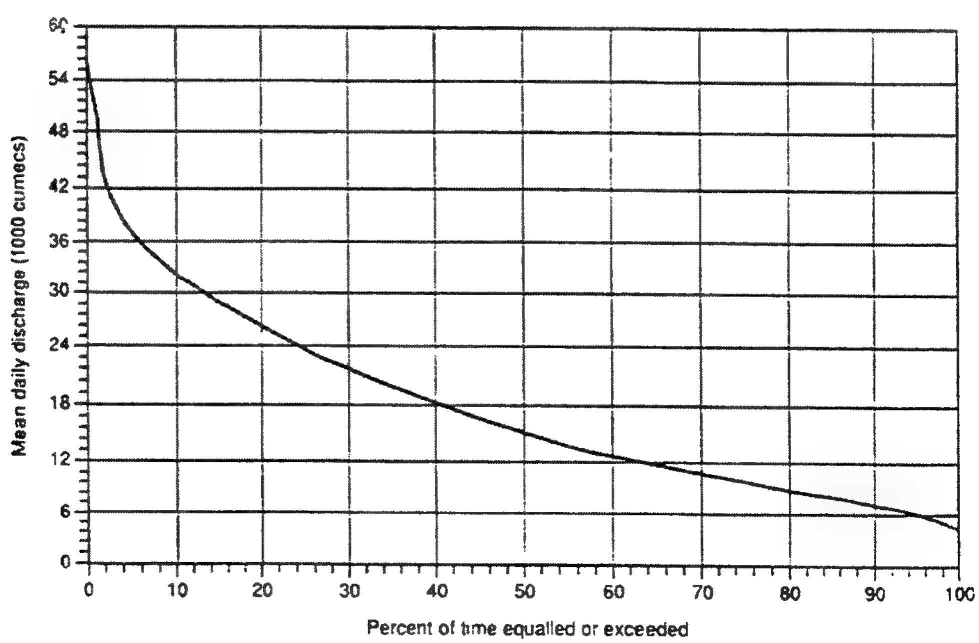

Figure 9. Flow-duration curve for mean daily discharge: Lower Mississippi River at Vicksburg, 1950-1982 (Biedenharn and Thorne 1994)

Bed-material load rating curve

Sediment-transport data were also obtained from the Vicksburg gauging station. The period of record was 1969 to 1979, as this was the only period for which measured sediment-transport records were available. Typically, sediment load was measured weekly. Robbins (1977) provides a detailed description of the sediment measurement program on the Lower Mississippi. The period of record includes both low runoff years and several events of high magnitude and long duration, so that the full range of sediment transporting flows is represented in the measured data.

The measured sediment loads were divided into two components: silt load consisting of particles less than 0.062 mm, and sand load consisting of particles coarser than 0.062 mm. The bed of the Lower Mississippi River is sand, so the sand fraction of the measured load was taken to represent the bed-material load. The silt load was taken to represent "wash load" and was excluded from the analysis.

There are no measurements of bed load, but according to the calculations of Toffaleti (1968) the bed load comprises less than 5 percent of the total sand load. Hence, it was deemed to be acceptable to ignore the bed load and to take the measured sand load as indicative of the bed-material load. The measured sand load data were used to construct a sand load rating curve for the study site (Figure 10).

Regression analysis of sand load as a function of discharge produced a coefficient of determination (r^2) of 0.82 and defined the bed-material load rating curve as:

$$Q_s = 0.00000513\, Q^{2.42} \text{ tonnes/day} \quad (1)$$

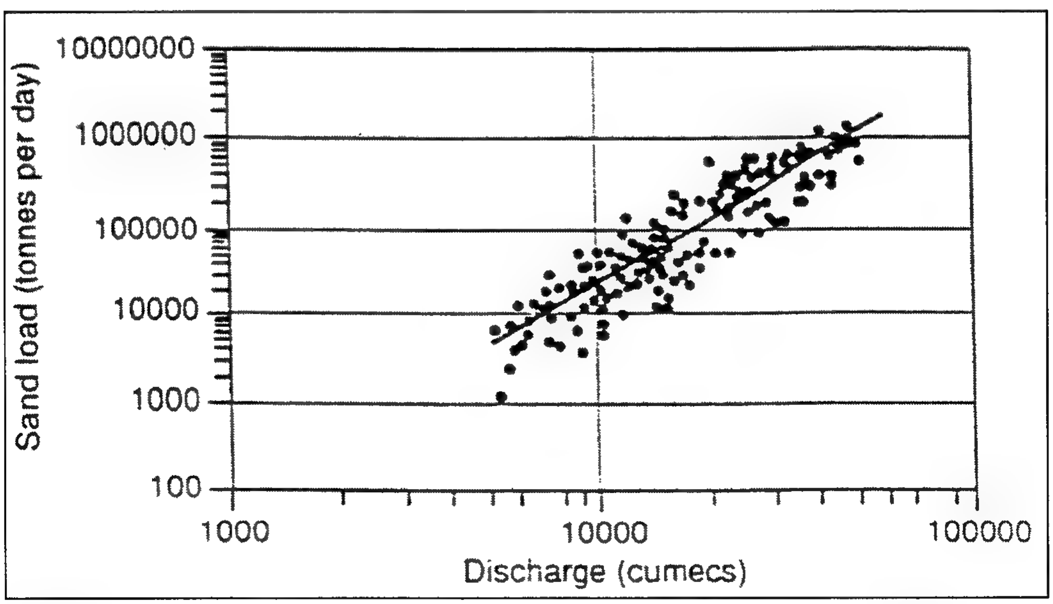

Figure 10. Sand load rating curve. Lower Mississippi River at Vicksburg 1969-1979 (Biedenharn and Thorne 1994)

Bed-material load histogram

The data in the flow-duration curve was divided into 50 equal classes ranging from 5 to 55,000 m^3/s and with a class width of 1,000 m^3/s. The bed-material transport rate for each discharge class (Q_s) was found from equation (1), with Q equal to the arithmetic mean discharge for that class. The quantity of bed-material load (in tonnes) transported by each discharge class was calculated by multiplying the frequency of each class (in days) by the bed-material transport rate for the average discharge (in tonnes per day). The resultant histogram is plotted in Figure. 11.

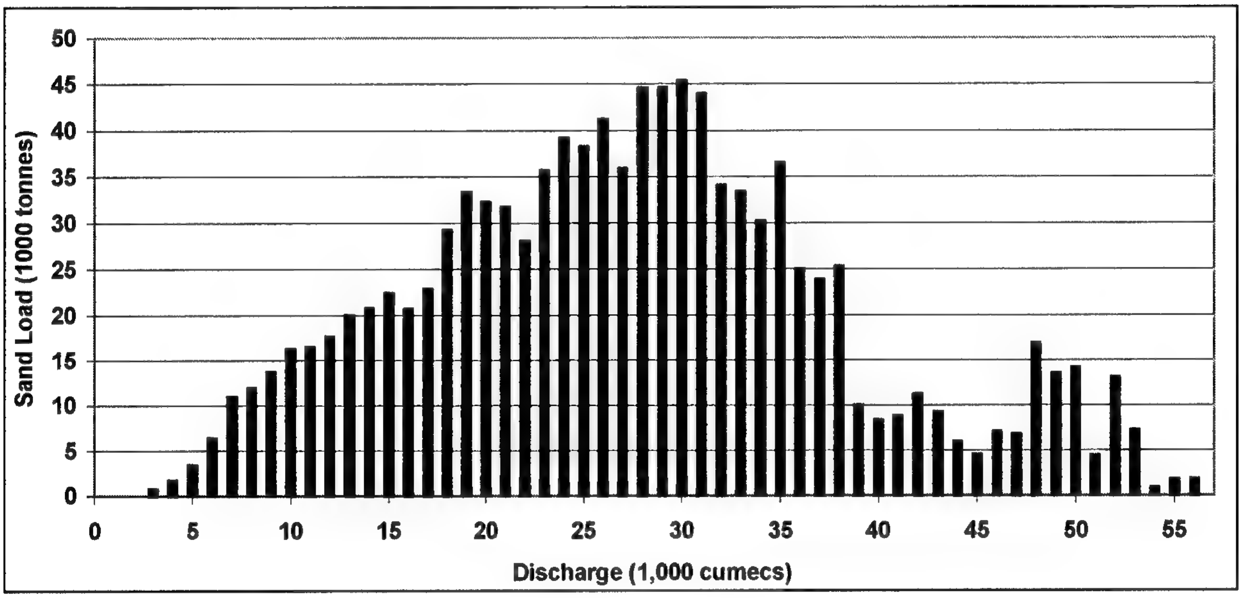

Figure 11. Bed-material load histogram. Lower Mississippi River at Vicksburg (Biedenharn and Thorne 1994)

Effective discharge determination

The peak of the histogram in Figure 11 is defined by the mean discharge of the modal class, which is 30,000 m^3/s. This defines the effective discharge.

Check if effective discharge is reasonable

In the Biedenharn and Thorne study, the effective discharge calculation was also performed for gauging stations at Arkansas City, AR (upstream of Vicksburg) and Natchez, MS (downstream of Vicksburg). No major tributaries enter the Mississippi River between these stations. Hence, it would be expected that the effective discharge should be the same at all three sites. This was in fact the case, illustrating consistency in the effective discharge analysis using three separate flow-duration and sediment-transport records.

Comparison of the water surface profile at the effective discharge ($30,000\ m^3s^{-1}$) to the long-channel distribution of bank top elevations is illustrated in Figure 12. The graph shows that bank top elevations are highly variable and can differ by 3 m or more between adjacent cross sections. This makes it difficult to assign a value to bankfull discharge for the reach. However, comparison of the water surface profile for the effective discharge to the bank top data indicates that the effective discharge forms a good lower bound to the scatter, indicating that the capacity of the channel is adjusted just to contain flows up to and including the effective flow. As discharge increases beyond the effective flow, water begins to spill over the bank tops at more and more locations.

The return period for the effective discharge (equal to or just less than one year) is consistent with the ranges given in "Guidance on return periods for the effective discharge," and its flow duration (equalled or exceeded on 13 percent of the time) is as expected for a river with a drainage area of approximately 3 million km^2 (Figure 8).

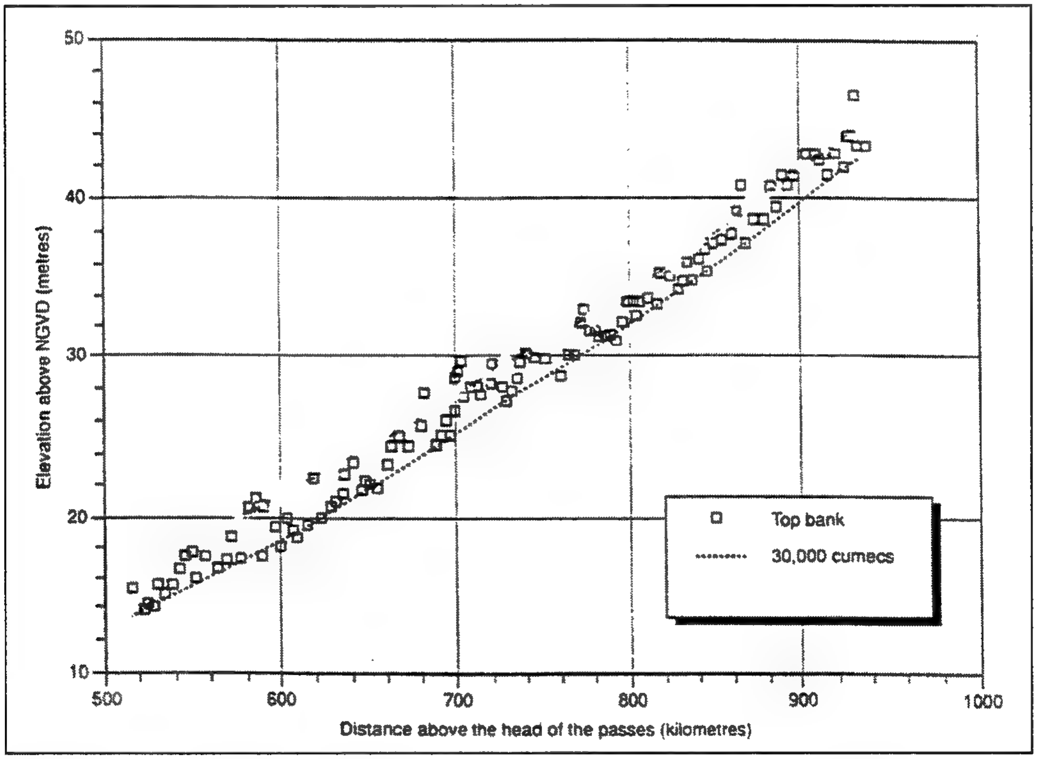

Figure 12. Long-channel variation in bank top elevations: Lower Mississippi in study reach (Biedenharn and Thorne 1994)

These checks indicate the calculated effective discharge is reasonable and support the accuracy of the analysis including the necessary assumptions concerning the use of measured sand load to represent the bed-material load.

Channel Management: Case Study of the River Blackwater, UK

The need for geomorphological studies to support sustainable engineering and management of rivers is now generally accepted (Gardiner 1991; Downs and Thorne 1996). Calculation of the channel- forming discharge and application of the principles of hydraulic geometry analysis can be useful in developing a sound understanding of the stability of an alluvial stream. The utility of this approach can be illustrated by brief reference to a case study of the River Blackwater, England. The study is reported in detail in a report by Hydraulic Research, Wallingford (1992) and in summary in a paper by Thorne, Simon, and Allen (1996).

The River Blackwater is a lowland stream in southeast England. In the 1960s and 1970s the channel was modified by engineering works installed as part of a series of flood defense and land drainage schemes. Subsequently, the channel required heavy maintenance to maintain a sufficient capacity for flood flows. More recently, steps have been undertaken to improve stream habitats by softening the impacts of engineering works, modifying the maintenance regime, and enhancing the channel environment.

As part of plans to restore the environmental function of the river, a geomorphological study was performed to establish how the existing, engineered channel differed morphologically from a natural, regime channel. An effective discharge calculation was performed using data from a nearby gauging station and the "expected" morphology for a natural, regime channel was established by applying the hydraulic geometry equations of Hey and Thorne (1986). Stream reconnaissance was performed to establish the morphology and bankfull dimensions of the existing, engineered channel using the method reported by Thorne (1998).

The effective discharge calculation showed that the channel-forming discharge was 3.65 m^3s^{-1}, compared to a bankfull capacity observed in the engineered channel of 16.4 m^3s^{-1}. The main morphological parameters calculated and observed were:

	Regime Channel	Engineered Channel
width	6.3 m	12 m
depth	0.59 m	1 m
x-section area	3.7 m^2	12 m^2
mean velocity	1.0 m/sec	0.3 m/sec

These contrasts between the regime and engineered channels were used to support the conclusion that the engineered channel was over-large in width, depth and area and that in-channel velocities were insufficient to transport the sediment load supplied from upstream. This explained its tendency for siltation and need for frequent maintenance.

On the basis of the geomorphological assessment, initial recommendations were proposed for morphological restoration of the channel to support the enhanced river environment. It was further proposed that the viability of these initial recommendations should be examined further to determine their feasibility for a restoration project.

The effective discharge was found in this application to be the key to deriving values for the dimensions of a natural regime channel appropriate to the current flow regime. This information was useful in highlighting the problems with the engineered channel and indicated the starting point for detailed design of a restored channel.

Channel Restoration Hydraulic Design

Introduction

The U.S. Army Engineer Research and Development Center is currently developing a systematic methodology for design of channel restoration projects. This methodology will be applicable to (but not limited to) channels that have a flood control component.

When hydrologic and sediment conditions are steady and the existing channel is stable, the existing channel wavelength and sinuousity should be maintained in any channel restoration scheme. The proposed methodology is intended for cases where a historically stable channel has been realigned creating instability, or where hydrologic and/or sediment inflow conditions have changed so much that the channel is currently unstable. Stability is defined as the ability to pass the incoming sediment load without significant degradation or aggradation. Bank erosion and bankline migration are natural processes and may continue in a stable channel. When bank line migration is deemed unacceptable, engineering solutions must be employed to prevent bank erosion. Bank protection technology is addressed by Biedenharn et al. (1997).

Hydraulic design methodology

Identify objectives. The first step in the methodology, as with any engineering project, is to clearly define project objectives. Is the objective to create an aesthetic setting, to create a natural setting, to enhance fish or wildlife habitat, to prevent bank erosion or channel degradation, or is it something else? Although these objectives could all conceivably be considered channel restoration, they are not necessarily compatible.

Geomorphic analysis. The hydraulic design of a channel restoration project should be preceded by a study of the watershed in order to determine the relationship of the stream to the rest of the hydrologic and geomorphologic system. If the stream is unstable, trends and stages of geomorphic evolution

should be identified. A determination of the existing and desired ecosystem is also a necessary component of a channel restoration project.

Determine hydrologic regime. To provide long-term stability, a historical hydrograph or a flow-duration curve is required. These may be obtained from stream gauges or from regional analysis. A channel-forming discharge can be developed from this data. Current research from the Flood Damage Reduction Research Program at ERDC suggests that the effective discharge can be used to estimate the channel-forming discharge. The effective discharge is the increment of discharge that transports the most sediment on an annual basis and can be determined by integrating a sediment-transport rating curve with the annual flow-duration curve. This calculation requires a knowledge of the flow-duration characteristics, bed-material size distribution, and a sediment rating curve (either measured, calculated, or a combination thereof). It is important to attempt to verify this channel-forming discharge with field indicators of bankfull discharge. This may be difficult or impossible in an incised stream. This verification step may be complicated because it requires an estimate of channel roughness unless measured stage-discharge data are available. It is also prudent to check the recurrence interval of the effective discharge. In most cases, it should be between the one- and three-year peak frequency events.

Determine the design width of the channel. When channel width is not constrained by right-of-way limitations, the preferred method for determining the width is to use geomorphic principles. Several techniques are available for determining the width of a stable alluvial stream. In order of preference they are:

a. *Analogy method.* A width can be determined for the project stream by assigning a measured average width from a reference reach. The reference reach must be stable and have the same channel-forming discharge as the project reach. The reference reach may be in the project reach itself, upstream and/or downstream from the project reach, or in a physiographically similar watershed. Streambanks in the project and reference reaches must be composed of similar material, and there should be no significant hydrologic, hydraulic, or sediment differences in the reaches. This technique is inappropriate for streams where the reference reaches are in disequilibrium.

b. *Hydraulic geometry method.* Hydraulic geometry theory is based on the concept that a river system tends to develop in a predictable way, producing an approximate equilibrium between the channel and the inflowing water and sediment (Leopold and Maddock 1953). The theory typically relates the dependant variable, width, to an independent or driving variable, such as drainage area or discharge. Hydraulic geometry relationships have also been applied to other dependent variables such as depth, slope, and velocity. Hydraulic geometry relations are sometimes stratified according to bed-material size or other factors.

Hydraulic geometry relations can be developed for a specific river, watershed, or for streams with similar physiographic characteristics. Data scatter is expected about the developed curves even in the same

river reach. The more dissimilar the stream and watershed characteristics are, the greater the expected data scatter is. So-called "regional curves" would be expected to have a wide band of scatter. It is important to recognize that this scatter represents a valid range of stable channel configurations due to variables such as geology, vegetation, land use, sediment load and gradation, and runoff characteristics. The composition of the bank is important in the determination of a stable channel width. It has been shown that the percentage of cohesives in the bank and the amount of vegetation on the bank significantly affect the stable channel width.

c. *Analytical methods.* If a reliable width vs. effective discharge relationship cannot be determined from field data or in cases where there is significant sediment transport, analytical methods may be employed to obtain a range of feasible solutions. These are discussed in the next section.

General guidance is available in U.S. Army Engineer Manual EM-1110-2-1418 (1994), and Hey and Thorne (1986). Currently under development at ERDC are hydraulic geometry predictors for various stream types with different bank characteristics. These predictors include confidence limits and may be used for general guidance when site specific data cannot be obtained.

Calculate a stable channel slope and depth. Depth and slope should be calculated using analytical techniques. Analytical techniques are more reliable than hydraulic geometry relationships for establishing the relationships between channel-forming discharge and depth, slope or velocity. Analytical approaches calculate the design variables of width, slope, and depth from the independent variables of discharge, sediment inflow, and bed-material composition. Three equations are required for a unique solution of the three dependent variables. Flow resistance and sediment transport equations are readily available. Several investigators propose using the extremal hypothesis as the third equation (Chang 1980; White, Beltess, and Paris 1982; Millar and Quick 1993). However, extensive field experience demonstrates that channels can be stable with widths, depths, and slopes different from extremal conditions. Therefore, others propose using a hydraulic geometry width predictor as the third equation. The stable-channel analytical method (Copeland 1994) in the U.S. Army Engineer hydraulic design package SAM may be used to determine a depth and slope for the width selected in the previous section. This method is based on a typical trapezoidal cross section and assumes steady uniform flow. The method is especially applicable to small streams because it accounts for sediment transport, bed form and grain roughness, and bank roughness. This method uses the Brownlie (1981) sediment transport and roughness equations for sand bed streams and the Meyer-Peter and Muller (1948) sediment transport equation with the Limerinos (1970) bed resistance equation for gravel bed streams. This procedure assumes a fully mobile sand bed.

In coarse bed streams, where sediment transport is small, or in streams with bedrock outcrops or with cohesive beds, threshold design methods (e.g. Lane 1955; USDA 1977) may be used to calculate depth and slope. However, in sand bed streams, sediment transport is typically significant and an analytical

procedure that considers both sediment transport and bed form roughness is required.

Determine a stable channel planform. This step involves determining a meander wavelength, an appropriate channel length for one meander wavelength, and then laying out a planform. Meander wavelength, can be determined using hydraulic geometry techniques. The most reliable hydraulic geometry relationship is wave length vs. width. As with the determination of channel width, preference is given to wavelength predictors from stable reaches of the existing stream either in the project reach or in reference reaches. Lacking data from the existing stream, general guidance is available from several literature sources (e.g., Leopold, Wolman and Miller 1964). The channel meander length is simply the meander wavelength times the valley slope divided by the channel slope.

One way to lay out the planform is to cut a string to the appropriate length and lay it out on a map. Another, more analytical approach, is to assume a sine-generated curve for the planform shape as suggested by Langbein and Leopold (1966) and calculate *x-y* coordinates for the planform. This rather tedious numeric integration can be accomplished using a computer program such as the one in the SAM hydraulic design package. The sine-generated curve produces a uniform meander pattern. A combination of the string layout method and the analytical approach would produce a more natural looking planform.

In streams that are essentially straight (sinuosity less than 1.2) riffle and pool spacing may be set as a function of channel width. The empirical guide of 6-10 channel widths applies here, with the lower end for steeper channels and the higher end for flatter channels. Two times this riffle spacing gives the total channel length through one meander pattern.

Conduct a sediment impact assessment. The purpose of the sediment impact assessment is to assess the long-term stability of the restored reach in terms of aggradation and/or degradation and determine the magnitude of future maintenance problems. This can be accomplished using a sediment budget approach for relatively simple projects or by using a numerical model which incorporates solution of the sediment continuity equation for more complex projects. With a sediment budget analysis, average annual sediment yield with the design channel is compared to the average annual sediment yield of the existing channel, if the existing channel is stable, or of the upstream supply reach, if the existing channel is unstable. Large differences in calculated sediment yield indicate channel instability. This step is especially important if the restored reach is part of a flood damage reduction project. In such cases it may be necessary to design a channel that is less than ideal in terms of channel stability in order to achieve flood control benefits. Typically, a compound channel design provides the best combination of benefits.

The most reliable way to determine the long-term effects of changes in a complex mobile bed channel system is to use a numerical model such as HEC-6. River systems are governed by complicated dependency relationships, where changing one significant geometric feature or boundary condition affects other

geometric features and flow characteristics both temporally and spatially. Changes at any given location in a stream system are directly related to the inflow of sediment from upstream. This makes the application of the sediment continuity equation essential to any detailed analysis. The most significant of these relationships and the continuity of sediment mass are accounted for in the numerical model approach. The fact that application of a numerical sediment model requires knowledge of sediment transport and river mechanics should not be a deterrent to its use, and that knowledge is required for any responsible design work in a river system. It should be expected that an analysis of system response in a complicated system, such as a mobile bed river system, will require some engineering effort. That effort should be based on analysis of the physical laws that govern the system. The system cannot be expected to adhere to constraints placed on it in violation of natural physical laws, no matter how well intentioned or frugally those constraints were developed. The critical decision with respect to using a numerical model should be based on whether or not "significant" changes are expected to occur in the system as a result of the proposed design work. In the U.S. Army Corps of Engineers, this decision typically is reached in the reconnaissance level planning study using the sediment impact assessment approach.

Effective Discharge Calculation in Support of a Channel Restoration Evaluation: Case Study

Introduction

Modifications to a river system that are inconsistent with natural processes can lead to a series of complex responses throughout the system. If the imposed channel dimensions or environmental features are not commensurate with the position of the restored reach in the fluvial system, the channel may adjust to a more stable form. Natural rivers are never in a state of continuous equilibrium but a variable, shifting equilibrium, or quasi-equilibrium (Langbein and Leopold 1964). Subsequently, channel forms constantly adjust around a medium to long-term average condition. In some cases insensitive river engineering can act as a catalyst within dynamic, metastable equilibrium (Schumm 1975) to carry the system over a geomorphic threshold into a new equilibrium regime. The enhanced channel design procedure presented here uses confidence bands to derive stable channel dimensions within the range found in nature. Using this principle, the river is "directed" towards a stable channel configuration, suitable for the target "type" of channel, but is encouraged to participate in its own recovery. Designing outside the stable limits may impose an unstable condition that can lead to evolution towards a new metastable equilibrium regime.

A case study is presented illustrating calculation of the effective discharge and also demonstrating a technique adopted to validate restored channel geometry in terms of medium to long-term equilibrium sediment conveyance by comparing the range of sediment-transporting flows in the supply reach with that of the restored channel.

Restoration of Willful Creek

The headwaters of Willful Creek are located in the Piedmont zone of the eastern United States and the majority of the system is found in the Coastal Plain. The drainage area upstream of a gauging station located immediately downstream from the project reach, is 12.25 km^2. There is only one significant tributary upstream from the project reach, which is gauged near the confluence and contributes considerably to the sediment budget. The drainage system is characterized by a high sediment load of sandy-gravel material pulsed through the system by a flashy flow regime and a relatively steep energy gradient.

Although field reconnaissance revealed that many streams in this coastal zone appear to be approaching a new state of equilibrium following the period of urbanization, a number of sites have been targeted for restoration to advance this recovery process and recreate stable channel configurations without compromising the designated level of flood protection. A 1.5 km reach of Willful Creek was restored in September 1996. The prerestoration channel morphology was characterized by low sinuosity and poor depth diversity as a result of previous channelization works.

The objectives of the channel design were to: recreate the diverse structure and function of a meandering channel to a river system of relatively low sinuosity; protect the bank lines from erosion; improve the aesthetic quality and amenity value of the stream within an urbanized watershed and maintain the present level of flood protection with embankments. The restored channel was designed to be static-stable, that is minimizing aggradation and degradation, while inhibiting the migrating tendency of a natural meandering river by protecting the bank lines from erosion. The restoration design, included:

a. A low flow channel with wide, shallow point bars within rock-lined embankments designed to contain the 50-year recurrence interval flood.

b. Increased sinuosity from approximately 1.05-1.1 to 1.5-1.7. This led to a decline in slope from approximately 0.0038 to 0.0025.

c. Decreasing meander wavelength from approximately 370 to 90 metres.

d. Restructuring in-stream morphology with asymmetrical cross sections around bendways and uniform cross sections at meander crossings.

e. Low stage rock vortex weirs at meander crossings to control the grade.

f. Root wads and riprap around bendways to prevent bank erosion and lateral shift in planform.

g. Willow planting to stabilize the wide, shallow point bars.

Observations both upstream and downstream from the restored reach revealed a considerably lower degree of sinuosity than that restored with an

almost straight alignment and occasional alternate bar features. Therefore, the restoration involved meander creation or enhancement rather than reinstatement.

Post-project channel change

Sediment impacts. Post-project reconnaissance revealed significant planform and cross-sectional channel change. In particular the stream has reduced its sinuosity from that constructed and it has experienced considerable sedimentation in the bendways. Cross-sectional surveys were undertaken at both a representative bend apex and crossing within the restored channel. Considerable aggradation, at both the bend apex and crossing sections, has occurred during the post-project period, between September 1996 and November 1998 (Figure 13). The morphological change is summarized in Table 1. The low flow channel has straightened by eroding through the unprotected sandy point bars. Post-project channel change can be summarized as: significant aggradation at bends and crossing; reduced sinuosity and channel steepening, via redistribution of sediments, and; isolation of the designed meander bendways as pools are filled and the thalweg adopts a straighter alignment.

Table 1
Post-Project Channel Change at a Representative Bend Apex and Crossing (specific gravity of bed-material is 2.65, density of water is 1,000 kg m^3)

Cross Section	Bend Apex	Crossing
Volume change (m^{3}s^{-1} per unit length)	5.01	2.50
Aggradation (tonnes per unit length)	13.29	6.63
Aggradation rate (tonnes yr^{-1} per unit length)	6.05	3.01

Recovery mechanisms. In summary, the energy of the restored channel was not sufficient to transmit the magnitude of sediment transported from upstream. The restored reach was not designed as a component within the broader river system and as a result the reach has acted as a sediment bottleneck which prompted a complex series of channel changes following project implementation. The degree of post project channel change may also have been amplified by the fact that bankside vegetation probably did not have time to establish before widening and straightening began. Although the restored channel was intended to be static-stable, the shallow, wide point bars were not stabilized sufficiently to withstand the erosive force of high flow events.

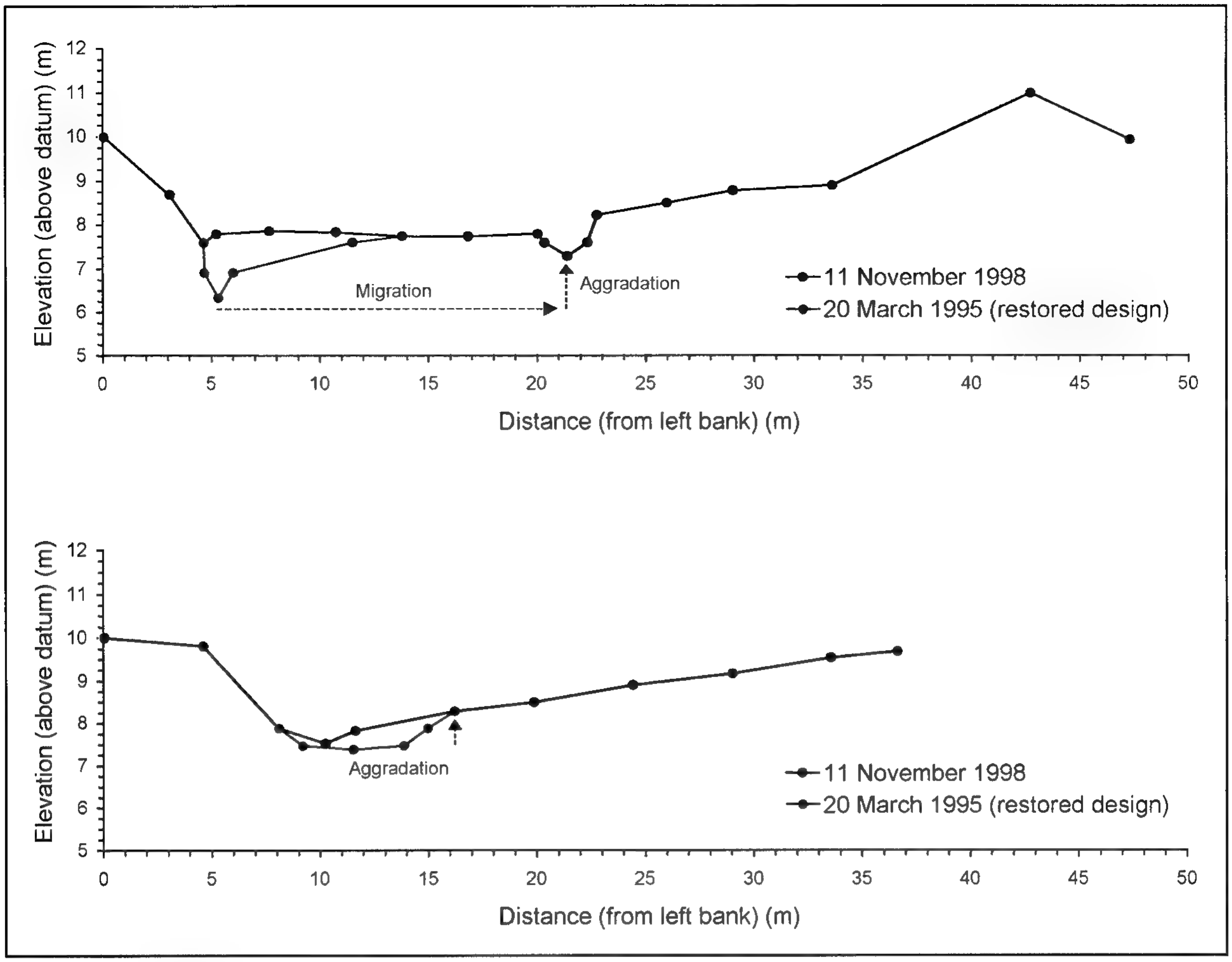

Figure 13. Design cross sections and post-project channel change: i) above: bend apex; ii) below: meander crossing (200 percent vertical exaggeration)

Channel restoration design procedure

Channel restoration design is the reconstruction of a river channel to a geometric configuration which is self-sustaining and in balance with imposed flow and sediment regimes and the character of the catchment landscape (Soar et al. 1998). Techniques to design restored channels are often based on a combination of field experience, reference reach observations and basinwide regime-type curves. While these approaches can yield appropriate target channel dimensions in some cases, they do not explicitly account for upstream sediment supply into the restored channel and the capacity of the restored reach to transmit sediment to the channel downstream. If sediment transport continuity through the restored reach is not achieved, it is unlikely that restored channel dimensions will be stable.

An enhanced channel design procedure currently in development (Soar et al. 1998; Copeland and Hall 1998) assesses sediment transport using a one-dimensional analytical method (Copeland 1994) that simultaneously solves flow resistance, sediment transport and hydraulic geometry equations at the effective discharge within designated confidence limits. Two important stages of the

design procedure are the calculation of the effective discharge, which is derived from magnitude-frequency analysis in the supply reach, and a sediment budget analysis to derive a Capacity-Supply Ratio (CSR) and verify whether the restored channel dimensions will minimize aggradation and degradation over the medium to long-term. The SCR may be used as a basis for refining the design slope to ensure reach-average dynamic stability and can help direct post-project maintenance of short-term channel change.

Supply reach magnitude-frequency analysis

A supply reach analysis is undertaken to describe the distribution of sediment-transporting flows and calculate the effective discharge, which are input to the restored channel from upstream. The effective discharge is used as the channel-forming discharge in the design procedure. Assessment of the sediment load entering the restored channel is necessary to ensure that channel stability is maintained within the restored reach, in terms of near zero net aggradation or degradation over the medium to long-term. Magnitude-frequency analysis requires a record of flow events and a sediment-rating relationship to generate a histogram of sediment-transporting flows for the reach of interest. If sediment transport data are unavailable, a sediment frequency histogram can be derived using a representative cross section and appropriate sediment transport equations.

Although Willful Creek is gauged immediately downstream from the restored channel, reconnaissance upstream of the restored reach failed to identify a suitable stable site in the immediate supply reach. Hence, a modified procedure was used to synthesize a sediment discharge histogram and effective discharge for the restored reach from available flow data and surveyed cross sections upstream of the tributary confluence. In the absence of measured load, (Meyer-Peter and Müller 1948) the bed-load equation was adopted to derive a sediment frequency histogram and determine the effective discharge. The Limerinos equation (Limerinos 1970) was used to characterize the roughness of the bed and generally yielded a composite Manning n-value of approximately 0.030 for the bed portion of the channel. The channel banks were assigned a Manning n-value of 0.085, which is suitable for moderately dense scrub with some trees. Initially, a flow-frequency histogram was derived using 25 class intervals ranging from the critical discharge for sediment transport to the maximum-recorded discharge. As the effective discharge could not be readily defined, the number of discharge classes was incrementally increased until a definitive peak on the sediment frequency histogram, giving an effective discharge 29.8 m^3s^{-1} with 30 arithmetic discharge classes (Figure 14).

Simulated channel restoration design

The enhanced channel restoration design procedure was applied to calculate depth and slope at the effective discharge using the Meyer-Peter and Müller (1948) bed load equation and the Limerinos (1970) flow resistance equation, both suitable for gravel-bed rivers. Confidence bands for stable bankfull width were derived from modified Hey and Thorne (1986) hydraulic geometry equations suitable for streams with well developed riparian vegetation and greater than

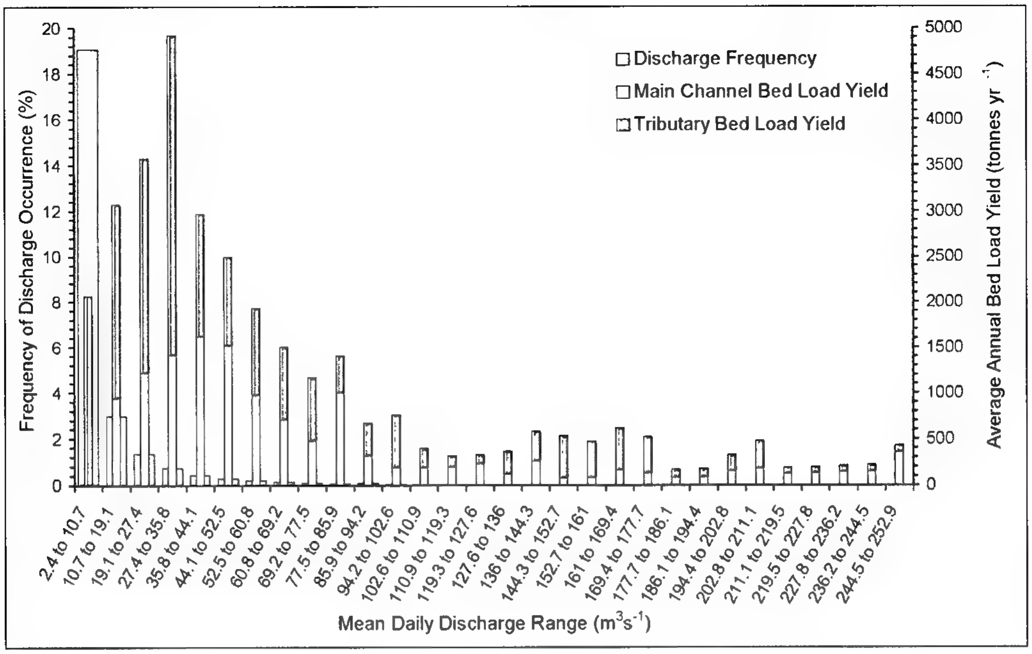

Figure 14. Supply Reach Magnitude-Frequency Analysis derived from stable reaches in the tributary and main channel upstream of the tributary confluence

50 percent tree/shrub cover. The simulated design assumes moderately rough banks with a Manning n-value of 0.085 and side slopes of 1.0.

Figure 15 presents the results of the analytical design in terms of a stable width-slope curve (primary axis) and stable width-depth curve (secondary axis). Suitable design solutions are located within the 95 percent confidence band. The chart shows that the restored design slope of 0.0025 underestimates the simulated range of slopes within the confidence band. This indicates that aggradation would be expected in the restored channel. The valley slope through the restored reach is estimated as 0.0043, giving the constructed restoration design a sinuosity of approximately 1.7, which is significantly greater than that calculated using the enhanced design procedure. This may explain the observed channel response through straightening. Table 2 presents a summary of the restored and simulated design parameters.

Sediment budget assessment: Capacity-Supply Ratio (CSR)

The potential success of a river project is often defined in terms of performance based on a single flow event and the sediment load transported by this event. This approach does not account for the potential for instability driven by other flow events in the long-term record. The potential for restoring sediment continuity through the restored reach requires an assessment of the sediment budget, which may be determined by the magnitude and frequency of all sediment-transporting flows. To attain geomorphic stability in the medium to long-term, the mean annual sediment load for the restored channel (capacity) must match the mean annual sediment load in the supply reach (supply).

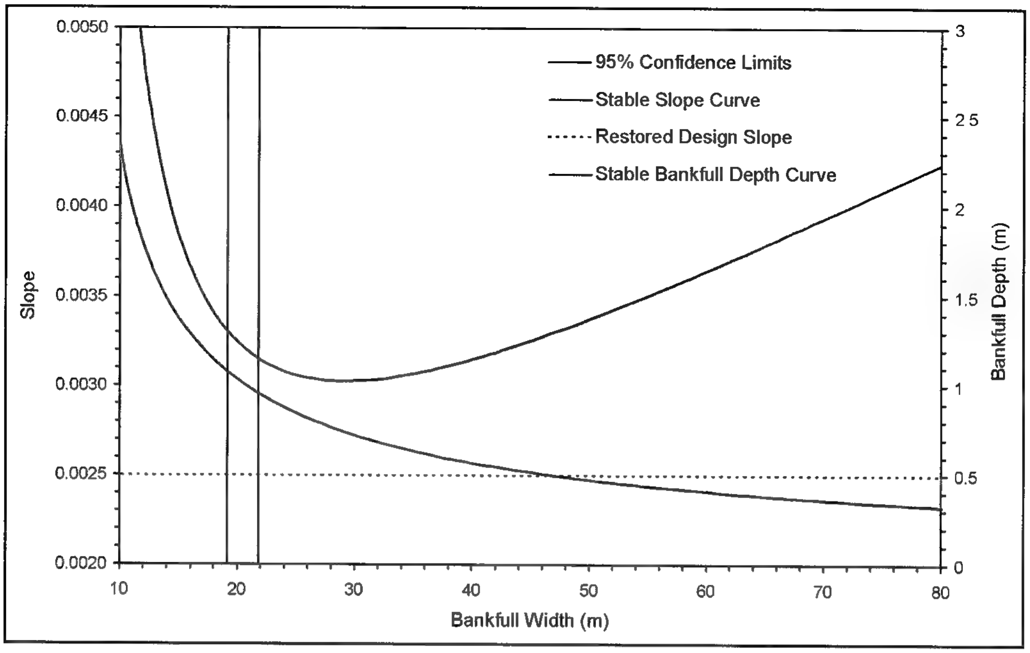

Figure 15. Stable width-depth-slope diagram. The range of stable slope (primary axis) and depth (secondary axis) are shown between 95 percent confidence intervals of the mean response

Table 2
Comparison of the Restored Channel Design with the Simulated Design from the Enhanced Design Procedure

Design	Width (m)	Mean Depth (m)	Slope	Sinuosity
Restoration	24.5	0.90	0.0025	1.7
Simulation	20.43 (19.17 to 21.82)	1.01 (0.96 to 1.20)	0.00322 (0.00315 to 0.00350)	1.29 (1.26 to 1.40)

Note: Width and depth refer to bankfull reference level. Values in parentheses are within 95 percent confidence limits of the mean response.

A Capacity-Supply Ratio (CSR), may be calculated as the bed-material load transported through the restored reach by the natural sequence of flow events over an extended time period divided by the bed-material load transported into the restored reach by the same flow events over the same time period. These loads are calculated by a numerical integration of a sediment-transport rating curve and the flow duration curve. A successful project design has a CSR close to unity. Values greater than 1.0 indicate potential degradation and values below 1.0 indicate potential aggradation. The CSR is used at the end of the design procedure as a closure loop to: validate the efficacy of the restored channel geometry; identify flows which may cause aggradation or degradation over the short term, and; recommend minor adjustments to the channel design to ensure that dynamic stability will be ensured over the medium to long-term. The CSR can be used to refine the design width, depth and sinuosity (and hence slope) to bring the CSR closer to unity and improve stability.

Achieving an optimum CSR, within 10 percent of unity, should ensure dynamic stability while allowing the river itself to recover some of the fluvial detail that cannot be designed by the engineer. It may be possible to adjust the design parameters within the designated level of confidence to achieve an optimum CSR, but if this cannot be achieved, the slope should be delicately increased or decreased appropriately until the CSR is in the optimum range. Refining the design slope will not affect the effective discharge in the restored channel. The CSR was used in this study to determine the success of the actual restored channel and that simulated from the enhanced design procedure. Comparison of sediment capacity and supply for the actual restored design revealed a CSR of 0.64: that is, the restored channel has the potential for approximately 36 percent of the input load to be deposited in the restored reach over the medium to long-term. This result is consistent with the observed aggradation in the restored meander bends. The CSR for the initial simulated design is 0.90, using mean values of width, depth and slope within the 95 percent confidence band. By slightly increasing the slope from 0.00307 to 0.00324, the CSR can be increased to unity.

The sediment capacity-supply analysis reveals that the restored alignment was too sinuous for the prevailing flow regime and sediment supply. A dynamically stable channel requires a lower sinuosity (approximately 1.33), which is similar to that observed upstream. Notably, the CSR is derived from a simple one-dimensional technique and is based on the total bed-material load transported. Disparities between capacity and supply within the sediment-frequency histogram of Figure 16 show a potential for some minor channel change in the short term.

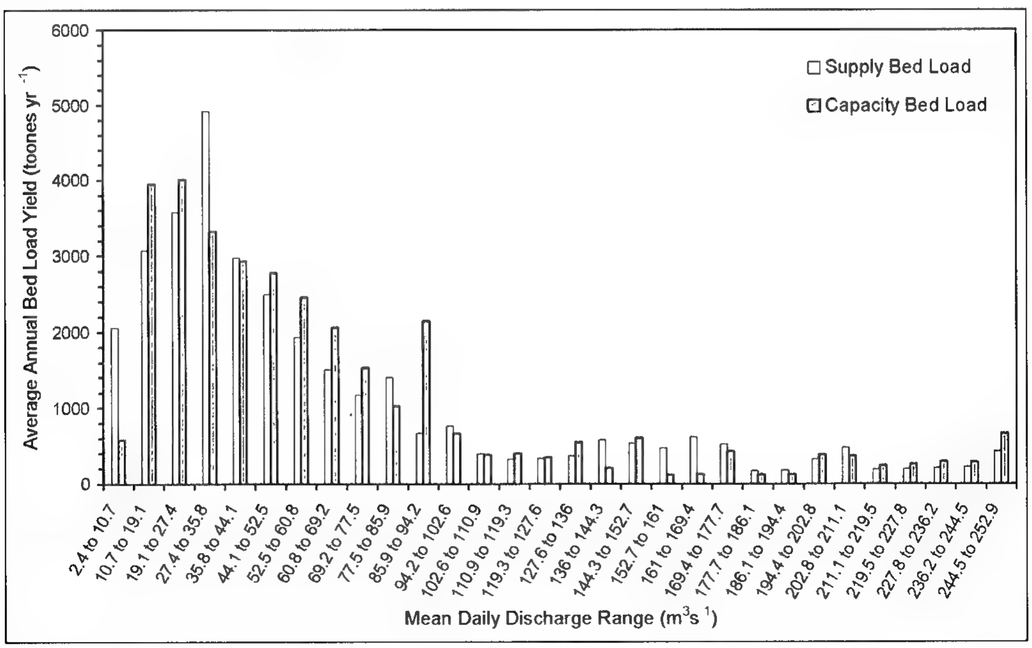

Figure 16. Comparison of sediment supply and capacity for the enhanced design based on 30 arithmetic discharge classes and increased slope of 0.00324, CSR is 1.00. The minimum discharge is the critical discharge for sediment transport in the supply reach

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Glossary

1. Channel Forming Discharge Concepts

1.58-Year Return Period Discharge ($Q_{1.5}$)
The discharge with a return period of 1.58 years, derived from the observed annual maximum flow series. Also called the *most probable annual flood.* Results of research on the use of $Q_{1.5}$ in dominant discharge analysis are reported by Hey (1975) for the UK and Leopold, Wolman, and Miller (1964) for the USA.

2-Year Return Period Discharge (Q_2)
The discharge with a return period of 2 years, derived from the observed annual maximum flow series. Results of research on the use of Q_2 in American rivers are reported by Biedenharn *et al.* (1987).

Bankfull Discharge (Q_b)
The maximum discharge which can be contained within the channel without over-topping the banks. Leopold, Wolman, and Miller (1964) proposed that this flow is responsible for forming and maintaining the morphology of the channel. Bankfull stage refers to the water surface elevation during bankfull flow and can be identified from various criteria (Williams, 1978). Research papers reporting the use of Q_b include: Leopold and Wolman (1957), Andrews (1980), Charlton, Brown, and Benson (1978), and Hey and Thorne (1986).

Channel-Forming Discharge
The discharge that most efficiently drives the fluvial processes responsible for forming and maintaining the main morphological features and dimensions of the channel. Synonymous with *dominant discharge.*

Design Discharge
The steady discharge used in the engineering design of a stable channel or flood defense scheme to define the upper boundary of the operating range of discharges for the project.

Discharge
The volume of water passing through a cross section in a stream per unit time. Usually expressed in cubic metres or cubic feet per second.

Dominant Discharge (Q_{dom})
The single, steady discharge which would produce the same cross-sectional morphology, alluvial features, planform geometry and dimensions as those generated by the actual flow regime (Inglis 1949).

Effective Discharge (Q_e)
Discharge responsible for transporting the largest fraction of the bed-material load in a stable channel over a period of years (Andrews 1980). Defined by the peak in a histogram of bed-material load versus discharge developed using the principles of magnitude and frequency analysis (Wolman and Miller 1960).

Flow doing most work
The steady discharge which performs the most geomorphic work, where work is defined in terms of sediment transport (Leopold and Miller 1960).

Mean Annual Discharge (Q_{ma})
The yearly-averaged discharge. Papers reporting research involving Q_{ma} include: Carlston (1965, 1969); Dury (1964); Leopold and Maddock (1953); Schumm (1971).

Mean Annual Flood ($Q_{2.33}$)
The discharge corresponding to the probability of exceedance of the mean annual flood event in a Gumbel extreme value type 1 probability distribution (EV1) derived from the observed annual maximum flow series. This event has a recurrence interval of 2.33 years. Papers reporting research involving $Q_{2.33}$ include Brush (1961) and Ferguson (1973).

Most Probable Annual Flood ($Q_{1.58}$)
The discharge corresponding to the probability of exceedance of the modal annual flood event in a Gumbel extreme value type 1 (EV1) derived from the observed annual maximum flow series. This event has a recurrence interval of 1.58 years. Papers reporting research involving $Q_{1.58}$ include Woodyer (1968) and Dury (1973).

2. Sediment load

Bed Load
Component of the *total sediment load* made up of sediment particles moving in frequent, successive contact with the bed (Bagnold 1966). Transport occurs at or near the bed, with the submerged weight of particles supported by the bed. Bed load movement takes place by gravitational processes of rolling, sliding or saltation.

Bed-material Load
Portion of the *total sediment load* composed of grain sizes found in appreciable quantities in the stream bed. In gravel-bed rivers the bed-material load moves as *bed load*, but in sand-bed streams significant quantities of bed-material load move as *suspended load*.

Fine Material Load
Portion of the *total sediment load* composed of particles finer than those found in the stream bed, and frequently assumed to be the fraction finer than 0.062mm. Often synonymous with *wash load.*

Measured Suspended Load
Portion of the *total sediment load* measured by conventional suspended load samplers. Includes a large proportion of the *suspended load* but excludes that portion of the suspended load moving very near the bed (that is, below the sampler nozzle) and all of the *bed load.*

Sediment Concentration
The concentration of sediment in the stream represented by the ratio of *sediment discharge* to the water *discharge*. Usually expressed in terms of milligrams per litre or parts per million (ppm). It is normally assumed that the density of the water-sediment mixture is approximately equivalent to the density of the water. This assumption is acceptable if the concentration is less than 16,000 mg/l.

Sediment Discharge
The mass of sediment that passes through a cross-section in a stream per unit time. Usually expressed in kilograms per second or tonnes per day.

Suspended Bed-material Load
That portion of the *bed-material load* that is transported in suspension within the water column.

Suspended Load
Component of the *total sediment load* made up of sediment particles moving in continuous suspension within the water column. Transport occurs above the bed, with the submerged weight of particles supported by anisotropic turbulence within the body of the flowing water.

Total Sediment Load

The total mass of granular sediment transported by the stream. Can be broken down by source, transport mechanism or measurement status as:

1. *Bed-material load* + *wash load*, or
2. *Bed load* + *suspended load*, or
3. *Measured load* + *unmeasured load.*

Unmeasured Suspended Load
That portion of the *total sediment load* that passes beneath the nozzle of a conventional suspended load sampler. It consists of near-bed suspension load and *bed load.*

Wash Load
Portion of the *total sediment load* composed of grain sizes finer than those found in appreciable quantities in the stream bed. The sum of *bed-material load* and *wash load* makes up the total sediment load.

3. Other terms

Ephemeral Stream
A water course in which channel processes and morphology are significantly affected by the fact that the discharge of water is intermittent. To be comparable with the definition of a *perennial stream*, this may be taken as a water course which exhibits a measurable surface discharge less than 80 percent of the time (Osterkamp and Hedman 1982).

Hydraulic Geometry
A geomorphological expression introduced by Leopold and Maddock (1953) to describe the morphology of an alluvial river as a function of dominant discharge. The concept is similar to *regime theory*, but differs in the way that the *dominant discharge* is expressed. With respect to the hydraulic geometry of an alluvial river, the *dominant discharge* is the single flow event which is representative of the natural sequence of events which actually occur. Regime theory was developed for canals, which do not experience a range of flows. Hence, the *dominant discharge* for regime theory is the steady, operating discharge.

Flow Duration Curve
A graphical representation of the percent of time (x-axis) that a specific discharge (y-axis) is equalled or exceeded during the period of record for which the curve was developed.

Perennial Stream
A stream which exhibits a measurable surface discharge more than 80 percent of the time (Osterkamp and Hedman 1982).

Regime Theory
A self-formed alluvial channel is in regime if there are no net changes in discharge capacity or morphology over a period of years. The concept was originally developed by engineers designing canals to convey a steady discharge with neither erosion or siltation in India and Pakistan (Kennedy 1895; Lindley 1919) and, later, in North America (Blench 1957).

Sediment Rating Curve
A graphical representation of the non-linear relationship between *discharge* (x-axis) and *sediment discharge* (y-axis).

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14. ABSTRACT
This report presents a procedure for calculating the effective discharge for alluvial rivers. An alluvial river adjusts the shape of its channel to the wide range of flows that mobilize the boundary sediments. However, in many rivers it has been shown that a single representative discharge can be used to determine a stable channel geometry. One method to determine this "channel-forming" discharge is based on the hypothesis that the discharge that transports the most sediment, over time, is the discharge that forms the channel. This is termed the effective discharge. Two other methods commonly used are the bankfull discharge and a discharge with a specific recurrence interval. While it may, under some circumstances, be possible to estimate the channel-forming discharge from the bankfull discharge, in practice, identification of bankfull stage in the field is often problematic. Even if bankfull stage can be identified, channel roughness and slope typically must be assumed to determine the bankfull discharge. Another method for determining channel-forming discharge is to assume a specific frequency from the annual flood peak frequency curve. However, there does not seem to be a recurrence interval that is generally applicable to alluvial rivers. The procedure for effective discharge calculation presented in this report is designed to have general applicability, have the capability to be applied consistently and to integrate the effects of physical processes responsible for determining channel dimensions. An example of the calculations necessary and applications of the effective discharge concept are presented.

15. SUBJECT TERMS

Bankfull discharge	Effective discharge	River engineering	River restoration
Channel-forming discharge	Hydraulic geometry	River management	Stable channel design

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